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SIR ISAAC NEWTON (1642-1727).

Greatest of natural philosophers; author of Principia; president of Royal Society twenty five years; member French Academy of Sciences; knighted 1705. Buried in Westminster Abbey.

TWENTIETH CENTURY TEXT-BOOKS

ELEMENTS OF PHYSICS

BY

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PREFACE

THE authors have prepared this book in the belief that physics should be so taught as to be a desirable and even essential subject for every pupil in the secondary schools. In its preparation they have therefore devoted much study to the conditions which obtain in the schools at the present time, and have endeavored to meet them.

The book is designed to provide a year's work for the class room, and only such matter has been introduced as is deemed appropriate for pupils of the high-school age and attainments. Laboratory exercises, questions, and problems given in a text-book are manifestly inadequate and unsatisfactory. The authors have therefore thought it preferable not to follow that course, but to amplify and make more thorough this part of the study in a separate volume, which is published under the title Physical Experiments, and is to be used concurrently with the text-book.

The relations of physics on all sides to human life and human interests have been emphasized. A text-book is much more readable if the material for the laboratory work is excluded from it. The text-book comprises the informational part of the subject, and the authors in this vol-

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ume have imparted to it much warmth and interest. The laboratory, on the other hand, deals with inductions and verifications, and its chief purpose is to make knowledge *real.* Both the laboratory and the class-room work are essential to a correct knowledge of elementary physics, and they should correlate in such a manner as to make the acquisition of that knowledge interesting as well as thorough. The work has been prepared with these essentials in view.

In the text-book the subject has been further humanized by the introduction of a few portraits, with brief sketches of the men who, by their researches, have contributed much to our knowledge of physics.

A further merit of the work is that the volume is compact. The subject-matter has been so disposed as to be most convenient for class exercises and for the arrangement of a study plan. A supplement in pamphlet form, containing helpful suggestions to teachers using the book for the first time, has been prepared, and will be furnished without charge.

August, 1900.

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PHYSICS: THE SCIENCE OF ENERGY

CHAPTER I

THE CONTENT OF PHYSICS

1. **The Two Elements in Physical Science.**—Let us call up before us a series of occurrences in the outer world:

An express train dashes past us. A waterfall plunges over a precipice. A breath of wind blows against our faces. A bird sings in the branch above us. A tree falls in the forest. A boy throws a ball. A child picks a flower.

These several events are apparently very unlike. They seem at first sight to have nothing in common; but when we look closer and reduce them to their simplest possible terms, we see that they are in reality very much alike. Each event contains the same two elements, matter and motion, and, from a physical point of view, that is all. Back of the matter and motion there may be motive and purpose, but we can only infer these. Our senses make direct report only of matter and motion. There are different sorts of matter and different degrees of motion, but the whole event in each case shows only these as the final outer content.

The study of natural events is therefore the study of matter and motion, and we must start out with clear general ideas concerning these two elements.

2. **Matter** may be defined for the present as that which occupies space. It naturally prevents anything else from occupying the same space. Hence, the essential properties

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of matter, or those properties without which we can not conceive matter to exist, are extension and impenetrability.

Matter makes itself known to us by the testimony of the senses. We see it, hear it, smell it, taste it, touch it. But observe that, after all, this is indirect testimony. These impressions are all of them simply brain impressions. We see, hear, smell, taste, touch, in our consciousness only. We can not assert, therefore, that matter exists apart from this consciousness. Science has nothing to say about the ultimate nature of matter. Science studies matter simply as a fact of human experience.

3. **Three States of Matter.**—Matter manifests itself in three states—as solid, liquid, and gas. These states of matter, as well as many of its motions, are best explained by assuming that matter is made up of extremely small particles, or units, which are called molecules. We shall study these later somewhat more in detail.

Solids, at the same temperature, have nearly constant volume and approximately constant form. Their molecules are so bound together that they can not change their relative positions except within very small limits.

Liquids, at the same temperature, also have nearly constant volume, but take at once the form of the vessels which contain them. Their molecules are free to move among themselves, but are not free to fly apart.

Gases have neither constant volume nor constant form. In consequence of the perfect mobility of their molecules, they will occupy any space into which they may be introduced, whatever its volume or form.

Liquids and gases, on account of the freedom of motion possessed by their molecules, are classed together as *fluids*.

4. **The Three States Continuous.**—It must not be thought for a moment that matter is sharply divisible into solids, liquids, and gases. On the contrary, these are only names for typical forms of matter. Within the same state we find

wide variations from the type, and even between the three states themselves we can set up no hard-and-fast lines.

5. **Radiant Matter.**—It has been thought that matter may exist in still a fourth state, and for this the name *radiant matter* has been proposed. It represents extreme dilution and mobility, and bears somewhat the same relation to gases that gases do to liquids. We shall study it later, when we come to consider Crooke's tubes.

6. **Motion** is change of position—a simple definition, but one which involves nearly the whole drama of Nature.

The absence of motion is *rest.*

We can only know whether a particle is in motion or at rest by comparing it with some other particle whose condition is known. But this in turn can only be known by a comparison with a third particle, and so on indefinitely. In the absence of any fixed reference point in the whole universe, we can only know *relative* motion and *relative* rest.

7. **Mass Motion and Molecular Motion.**—The motion of a body may be either of the whole, giving us mass motion; or it may be of the parts, giving us molecular motion.

When the motion is of the whole, and not too rapid, as when an apple falls to the ground or a ball is thrown through the air, we can directly watch the change of position. When the motion is too rapid for that, as in the passage of a cannon ball, we can still observe indirectly the change of position by observing the body first in one place and then in another.

If the motion is confined to the parts, it is more difficult to realize it. The body, as a whole, stands still, and we can not see the motion of the molecules. But this molecular motion is quite as important as the mass motion, since it is the source of all heat and light, and of much that is most interesting and beautiful in Nature. It is a motion which can not be observed directly, but nevertheless our knowledge of it is almost as definite and accurate as our knowledge of the larger visible movements.

8. **Force.**—The human mind has grown into the habit of hunting for causes back of all events. Motion is a very striking event. The mind, therefore, following its old habit, has long hunted for a cause of motion. It has found none. It has, however, imagined a cause, and called it *Force.*

Force may be defined as that which produces motion or pressure.

We shall have occasion from time to time to use the term Force, but we shall always have in mind the observable reality, motion.

9. **Energy.**—A body in motion, or a body in such a position that it is capable of motion, is said to possess *Energy.* The motion may be either mass motion or molecular motion: the term Energy applies to both.

A body can lose energy only by giving its motion to some other body, whose total motion will thus be increased. A body never loses all of its energy because it never loses all of its motion.

The term "energy" is not open to the same objection that "force" is. It is permissible to speak of the visible universe as a manifestation of energy.

10. **Matter and Motion.**—It is convenient for the purpose of study to speak of matter and motion as being the two elements in every event. But in Nature the two are not thus separated. Matter is always endowed with motion, and we only know motion as manifested in matter. When we grow wiser, we shall study the two as one experience. They are summed up in the term Energy.

11. **Physics.**—The study of events in terms of the matter and motion involved in them constitutes physical science. If we direct our attention chiefly upon matter, we have that aspect of physical science known as Chemistry.

Chemistry is the study of the composition of matter.

If our attention be concentrated upon the motion, we have that aspect of the science known as Physics.

Physics is the study of motion, and deals with matter only as the carrier of motion.

Physics is sometimes defined as the science of the properties of matter, since these depend upon its motions. It is also defined as the study of the forces manifested in matter. Perhaps it is best defined as the Science of Energy, or the study of matter in motion.

12. **Metaphysics.**—Turning back for a moment to the random series of events named in the opening paragraph, we see that in addition to the matter and motion involved in them, there is in some of them a certain human element, or what we may call a thought element. The express train represents a certain amount of matter moving in a certain direction at a certain rate of speed, but it also represents the intelligence which shapes and guides it, and the purpose which prompts the event. It is the same with the boy throwing the ball, and with the child picking the flower. This something, outside the matter and motion of the event, which we have called the motive, does not fall within the province of physics. It belongs to the domain of *Metaphysics.*

Metaphysics seeks to find a theory of reality. Physics does not attempt so difficult a search: it limits itself to the study of matter in motion, to the study of things as we see them, and is not at all concerned with the underlying reality. We are not concerned in physics with what things really are, but solely with their properties and behavior. Physics neither offers nor seeks an explanation of the universe. It leaves all such problems to metaphysics.

13. **The Eternal "Why."**—We shall not, therefore, find in physics any answer to the questions: What is matter? What is motion? What is heat, light, electricity? Physics defines them, but it does not tell what they *are*, for it does not know. Yet we shall try to show throughout the book, and notably in the concluding chapters, that the whole value of physics is human. It is worth studying, just because it

does make our world larger and more orderly and more beautiful, and not because physical facts have any value independent of their human application.

PROBLEMS.—1. Select five events and analyze them into their matter and motion content.

2. Name one event containing a thought element and analyze as before. Can the thought element be expressed in terms of matter and motion ?

3. If a monkey sit on top of a pole, and always face a man who walks around the pole, with his face always turned toward the monkey, can the man be said to walk around the monkey ?

4. Are the hub and the rim of a carriage wheel relatively in motion or at rest ?

5. When the dinner bell rings, is it a case of mass or molecular motion ?

6. Can you name any fact of which you are absolutely sure ?

REFERENCE.

Emerson's Essay on Nature.
First Steps in Philosophy: William M. Salter.

CHAPTER II

THE CONSTITUTION OF MATTER

Apparatus: Specimens of chemical elements and of simple and compound bodies. O and H generators or cylinders. Eudiometer tube. Hoffman apparatus for decomposing water, and a suitable battery.

14. **The Province of Physics.**—We have defined matter as that which occupies space, and prevents anything else from occupying the same space. It is made manifest to us through the senses.

Now, physics does not deal with matter as such. That is the province of chemistry. But physics does deal with matter as the carrier or vehicle of motion, and for this purpose must inquire very carefully into the constitution of matter.

15. **Simple and Compound Bodies.**—We know matter as solid, liquid, and gas. We can make many substances—such as water, for example—pass through all these three states. But if our power ends here, and we can not add or subtract anything, the water remains a stubborn fact in whatever state it exists.

We do observe, however, a marked difference in the behavior of substances. Some of them can not by any means now at our command be separated into different substances or constituents. We can get but one thing out of such a substance, and that is itself. Matter which is thus incapable of analysis into anything else is called a chemical *element.* There are about seventy elements so far discovered. A list of them will be found at the end of the chapter.

But there are other forms of matter which may be separated into two or more elementary constituents, and are therefore called *compounds.* Their number is infinite, but they all consist of combinations of the seventy elements. These compounds form nearly all the substances met with in every-day life, such as water, foods, wood, cloth, stone, brick, etc.

16. **Atoms and Molecules.**—We have no direct proof that matter is built up of distinct particles or units. As far as we can see, it is perfectly continuous, and occupies all of the space that it seems to occupy. But certain considerations—such as its contraction and expansion, the capacity of certain liquids to dissolve solids and gases, the ability of nearly all fluids and of some solids to transmit light, and many other phenomena which imply a large mobility in matter—have led to the thought that matter is made up of definite particles or units, and for these the names *atoms* and *molecules* have been proposed.

The *atom* is the smallest quantity of an element that can exist. It is indivisible and indestructible. Atoms of different elements have different weights. These are the so-called atomic weights of chemistry.

The *molecule* contains one or more atoms, and is the smallest quantity of matter that can have a separate existence. When the atoms are all alike, the molecule is elementary, and the substance which it forms is an element. When the atoms are unlike, the molecule is compound, and the substance is known as a compound body.

17. **Size of Molecules.**—It is not possible to see a molecule, even with the aid of the most powerful microscope. Various estimates of the size of molecules have been made by different physicists. The illustration given by Lord Kelvin is the most familiar. He suggests that if a drop of water were magnified to the size of the earth, its molecules would appear as large as tennis balls.

According to Maxwell, the very smallest particle that we can see contains from sixty million to one hundred million molecules.

18. **Mechanical Mixtures and Chemical Compounds.**—When we mix together two elements or compounds in such a way that their molecules remain unchanged, we call the result a mechanical mixture. This is the condition of the atmosphere. It consists for the most part of the two gases, oxygen and nitrogen, and the molecules of each gas remain distinct and separate. We speak of them as being free. When, however, the substances are so united that the original molecules are broken up and new ones take their place, we call the result a chemical compound. Thus, for example, when two volumes of the gas hydrogen are brought into contact with one volume of the gas oxygen in the cold, no matter how thoroughly they are shaken up, they remain a simple, mechanical mixture. But if now an electric spark be passed, or a flame applied, we have an explosion; the separate

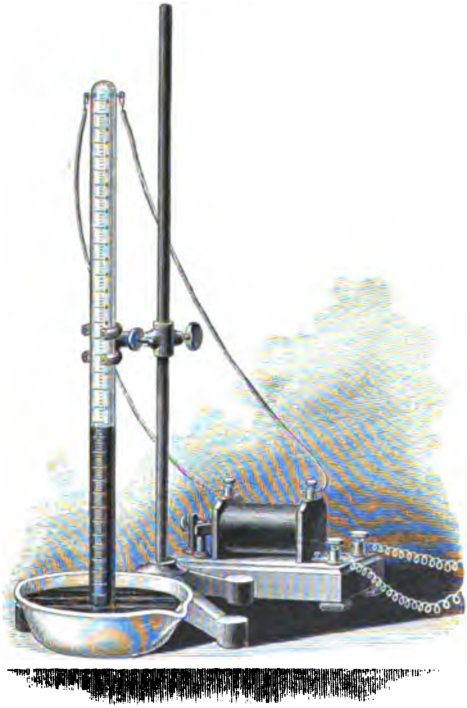

FIG. 1.—Eudiometer tube and induction coil.

molecules of hydrogen and oxygen are broken up, and in their place we find molecules of water vapor. We may represent this graphically as follows:

$$H_2 + H_2 + O_2 = H_2O + H_2O.$$

After the explosion our three molecules are built into two. Consequently, the water vapor occupies only two thirds the volume of the original gases, and is correspondingly denser. This may be illustrated by introducing two volumes of H and one volume of O into an eudiometer tube over mercury, and exploding the mixture by means of a spark from an induction coil.

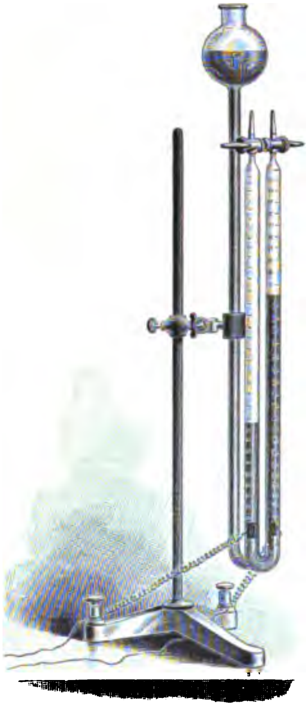

FIG. 2.—Hoffman apparatus for decomposing water.

19. **Physical and Chemical Changes.**—In terms of the molecular theory we call all changes in matter physical, which leave the molecules the same; and all changes chemical, in which the original molecules are broken up and new ones take their place.

Thus the passage of water through its three states is a purely physical change, while the decomposition of water into hydrogen and oxygen is a chemical change. The first is illustrated by the melting of ice and evaporation of the resulting water. The second can readily be shown by filling a Hoffman apparatus with acidulated water and passing an electric current through it for some time. Notice that the volume of the H is twice that of the O.

20. **Protyle.**—The atom which we have described above is the chemical atom, and by definition is indestructible. It is more reasonable to believe, however, that as we have only one power in the universe manifested in the different forms of energy, known as heat, light, sound, electric current, etc., so we have only one form of primary matter, and that the so-called elements are in reality compounds of this one primal unit. The name *protyle* has been suggested for it. According to this view, the chemical atoms are made up of still smaller physical atoms, and are consequently composed of the same primal stuff. They differ from one another only in their internal architecture, and hence in their capacities for motion. The difference in the behavior of the chemical atoms is therefore assumed to depend entirely upon the number and arrangement of the protyle atoms which go to make them up.

This view of matter is entirely theoretical. No one has ever isolated the molecule and atom, much less the physical atom of protyle. Nor have we any authentic record of the change of one chemical element into another. The old alchemists believed in the transmutation of the metals, and spent years in the vain attempt to change base metals into gold. Modern science hardly expects to accomplish this transformation, even though holding the view that iron and gold are made up of the same primal stuff. It does believe, however, that in the mightier laboratory of Nature such a precipitation of the primal matter into our so-called elements may have taken place, is perhaps taking place now in distant suns and stars, and that under suitable conditions these so-called elements may resolve again into the primal element.

21. **Doubt.**—We have spoken of molecules and atoms in some of the preceding paragraphs much as if they really existed. But modern science believes nothing of the sort. At best, our molecules and atoms are only shadows of conditions in matter which we do not yet understand. The

terms are convenient, and we must often use them, but they must be understood to be names for our ignorance rather than for our knowledge.

Professor Huxley says: "The primitive atomic theory, which has served as the scaffolding for the edifice of modern physics and chemistry, has been quietly dismissed. I can not discover that any contemporary physicist or chemist believes in the real indivisibility of atoms, or in an interatomic matterless vacuum."

And Professor Tait says: "An exact or adequate conception of matter itself, could we obtain it, would almost certainly be something extremely unlike any conception of it which our senses and our reason will ever enable us to form. . . . The discovery of the ultimate nature of matter is probably beyond the range of human intelligence."

22. **The Firm Ground in Physics.**—The fact that matter and motion must ever remain a profound mystery does not make the science of physics any less exact. It deals, not with the ultimate nature of matter and motion, but with their every-day manifestations, and these are capable of exact study and measurement.

23. **Table of Elements.**

NAME.	Symbol.	State at usual temperature and pressure.	Source.	Atomic weight.	Specific gravity.	Date of discovery.
ALUMINIUM....	Al	Solid.	Clay, etc.	27.0	2.58	1828
ANTIMONY..... (Stibium).	Sb	"	Sulphid ores.	120.0	6.7	1450
ARSENIC	As	"	" "	75.0	5.71	1694
Barium........	Ba	"	Heavy-spar, etc.	137.0	3.75	1808
BISMUTH.......	Bi	"	Sulphid ores.	208.9	9.8	1450
Boron.........	B	"	Borax.	11.0	2.6	1808
BROMINE.......	Br	Liquid.	Seaweed, etc.	79.95	3.19	1826
Cadmium	Cd	Solid.	Zinc ores.	112.0	8.65	1817
Cæsium.......	Cs	"	Alkali salts.	132.9	1.88	1860
CALCIUM	Ca	"	Limestones, etc.	40.0	1.7	1808
CARBON........	C	"	Diamond, graphite, coal, etc.	12.0	Up to 3.5	Antiquity

Table of Elements (continued).

NAME.	Symbol.	State at usual temperature and pressure.	Source.	Atomic weight.	Specific gravity.	Date of discovery.
Cerium	Ce	Solid.	Rare earths.	140.2	6.7	1803
CHLORINE	Cl	Gas.	Common salt, etc.	35.45	2.45	1774
CHROMIUM	Cr	Solid.	Chrome iron ore.	52.1	7.3	1797
Cobalt	Co	"	Sulphid ores.	59.0	8.96	1733
Columbium	Cb	"	Rare minerals.	94.0	7.+	1801
COPPER	Cu	"	Native and sulphids.	63.6	8.9	Antiquity
Erbium	Er	"	Rare earths.	166.3	....	1843
Fluorine	F	Gas.	Fluor-spar, etc.	19.0	....	1771
Gadolinium	Gd	Solid.	Rare earths.	156.1	....	1886
Gallium	Ga	"	Zinc ores.	69.0	5.95	1875
Germanium	Ge	"	Rare minerals.	72.3	5.47	1886
Glucinum (Beryllium).	Gl	"	Beryl, etc.	9.0	1.85	1828
GOLD (Aurum).	Au	"	Native.	197.3	19.3	Antiquity
HYDROGEN	H	Gas.	Water, etc.	1.0	.069	1766
Indium	In	Solid.	Rare minerals.	113.7	7.4	1863
IODINE	I	"	Sea water, etc.	125.85	4.95	1811
Iridium	Ir	"	Native.	193.1	22.4	1803
IRON (Ferrum).	Fe	"	Oxide ores.	56.0	8.0	Antiquity
Lanthanum	La	"	Rare minerals.	138.2	6.1	1839
LEAD (Plumbum).	Pb	"	Sulphids, etc.	206.95	11.36	Antiquity
Lithium	Li	"	Alkali springs and Li mica.	7.02	.585	1817
MAGNESIUM	Mg	"	Limestones, etc.	24.3	1.75	1829
MANGANESE	Mn	"	Oxide ores.	55.0	7.2	1774
MERCURY (Hydrargyrum).	Hg	Liquid.	Native and sulphid.	200.0	13.596	Antiquity
Molybdenum	Mo	Solid.	Sulphid.	96.0	8.6	1782
NICKEL	Ni	"	Sulphids, etc.	58.0	8.9	1751
NITROGEN	N	Gas.	Air and saltpetre	14.03	.96	1772
Neodymium	Nd	Solid.	Rare earths.	140.5	6.5	1885
Osmium	Os	"	Native.	190.8	22.48	1803
OXYGEN	O	Gas.	Air, water, and most minerals.	16.0	1.1056	1774
Palladium	Pd	Solid.	Native.	106.6	12.1	1804
PHOSPHORUS	P	"	Phosphate earths	31.0	1.84	1669
Platinum	Pt	"	Native.	195.0	21.5	1741
POTASSIUM (Kalium).	K	"	Chlorid, etc.	39.11	.86	1807
Praseodymium	Pr	"	Rare earths.	143.5	6.5	1885
Rhodium	Rh	"	Native.	103.0	12.1	1804

Table of Elements (continued).

NAME.	Symbol.	State at usual temperature and pressure.	Source.	Atomic weight.	Specific gravity.	Date of discovery.
Rubidium	Rb	Solid.	Alkali minerals.	85.5	1.52	1860
Ruthenium	Ru	“	Rare earths.	101.6	12.26	1845
Samarium	Sm	“	“ “	150.0	.....	1879
Scandium	Sc	“	“ “	44.0	.....	1879
Selenium	Se	“	With sulphids.	79.0	4.5	1817
SILICON	Si	“	Quartz, etc.	28.4	2.48	1823
SILVER (Argentum).	Ag	“	Native and ores.	107.9	10.5	Antiquity
SODIUM (Natrium).	Na	“	Common salt, etc.	23.05	.97	1807
Strontium	Sr	“	Carbonate, etc.	87.6	2.5	1808
SULPHUR	S	“	Native, and as metallic sulphids.	32.06	2.07	Antiquity
Tantalum	Ta	“	Compound ores.	182.6	10. +	1802
Tellurium	Te	“	With sulphids.	125.0	6.23	1782
Terbium	Tb	“	Rare earths.	160.0	.....	1843
Thallium	Tl	“	“ “	204.18	11.19	1862
Thorium	Th	“	“ “	232.6	11.23	1828
Thulium	Tu	“	“ “	170.7	.....	1879
TIN (Stannum).	Su	“	Tinstone.	119.0	7.25	Antiquity
Titanium	Ti	“	Rare minerals.	48.0	.....	1789
Tungsten (Wolframium).	W	“	Lead and other ores.	184.0	19.26	1781
Uranium	U	“	Oxide ores.	239.6	18.69	1789
Vanadium	V	“	Ores of lead, etc.	51.4	5.87	1830
Ytterbium	Yb	“	Rare oxides.	173.0	.....	1878
Yttrium	Yt	“	“ “	89.1	.....	1828
ZINC	Zn	“	Zinc blende, etc.	65.3	7.12	1520
Zirconium	Zr	“	Rare oxides.	90.6	4.15	1824

NOTE.—The common elements are printed in small capitals, the rare elements in italics, and the remainder in ordinary type. The table follows F. W. Clarke, chemist of the United States Geological Survey.

PROBLEMS.—1. Select half a dozen common substances, and find out whether they are simple or compound.

2. Is brass a mechanical mixture or a chemical compound?

3. Write out the chemical reaction that will express the decomposition of water, starting out with two molecules and representing them by $2H_2O$.

4. When a steel bar is magnetized, is the change physical or chemical?

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CHAPTER III

PROPERTIES OF MATTER

APPARATUS: A set of minerals, representing the scale of hardness. Crystal models and, if possible, common crystallized minerals. Balance and suspended plate of glass (29). Jars of O and H. Solution of copper sulphate. Diffusion apparatus (34). Dialyzer. Capillary tubes. Mercury.

24. **Secondary Properties of Matter.**—In addition to its essential properties, extension and impenetrability, matter exhibits certain characteristic secondary properties. These are so named because they do not, like the essential properties, apply to all matter, but only to certain forms of matter. Thus, solids possess hardness, crystalline form, cohesion, adhesion, porosity, flexibility, elasticity, brittleness, malleability, ductility, and tenacity, while fluids exhibit diffusibility, viscosity, and capillarity; and all bodies—solid or fluid—separated in space, tend to move toward one another, a relation which we express by the word weight.

We may not say, however, that weight is an essential property of matter, since it is rather a relation than an indwelling property. A single body, alone in space, would have no weight.

Nor may we properly say that *inertia* is an essential property of matter, meaning by inertia the tendency of a body to remain in motion or at rest unless influenced by some other body, for this is simply to say that nothing happens without a cause—a statement that goes without saying.

Many of these secondary properties of matter are sufficiently explained if we simply know the meanings of the words themselves. Physics studies only those properties which are capable of measurement, or which take some knowable part in the drama of natural events.

25. **Hardness.**—By the hardness of a body we mean the difficulty of penetrating between its particles. We measure hardness by comparing bodies with a series of solids arranged by agreement in an ascending scale. That most commonly in use was proposed by Mohs, and is as follows:

1. Talc (soapstone). Easily scratched by the finger nail.
2. Gypsum. Scratched by the nail.
3. Calcite. Easily cut by knife.
4. Fluorite. Cut by knife.
5. Apatite. Difficultly cut by knife.
6. Feldspar. Cut by glass.
7. Quartz. Cuts glass.
8. Beryl.
9. Corundum.
10. Diamond.

This scale was meant for the use of mineralogists, and selects natural minerals rather than artificial products, partly because they are better suited to the purposes of mineralogy, and partly because their hardness is more constant.

The test of hardness is very important in determining minerals. Thus calcite (crystallized marble, $CaCO_3$) and quartz (rock crystal, SiO_2) have the same crystal form, and often look much alike. A simple test with the penknife serves to distinguish them.

26. **Crystalline Form.**—Many solid bodies exhibit definite geometric forms or crystals. The study of crystals—crystallography—is a very useful and a very beautiful branch of natural science. It is not known why substances take definite crystal forms. In doing so they usually increase in volume, as when water crystallizes into ice, and the pressure exerted by their particles is very great; pipes of lead, and even of wrought iron, burst with the freezing of the

water that they contain; the hardest rocks are split and torn into the tiny fragments which constitute soil, when the water in their crevices freezes; and the delicate lines in our printing types are filled out by the expansion of the crystallizing type metal.

Substances which have a cystalline structure often show a decided tendency to split along planes parallel to well-defined crystal faces. We call this *cleavage.* It is well seen in such minerals as mica, calcite, and feldspar.

Substances such as flint and opal, which show no crystalline structure, are called *amorphous.*

27. **Cohesion** is the name given to the bond which holds the molecules of a body together. It is strongest in solids and least in gases. The varying strength of cohesion gives us the different degrees of rigidity, tenacity, and hardness in bodies. When we break a substance we conceive that the molecules become so far separated that their cohesion is overcome. Once separated, cohesion can only be restored by bringing the molecules very close together again by some agent, such as heat. This is done when two pieces of wrought iron are welded together. The same thing takes place in the working of glass.

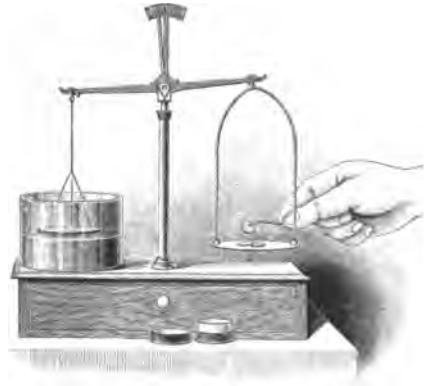

FIG. 3.—Showing adhesion between glass and water to be greater than cohesion in water.

The strength of materials depends upon their cohesion. It is measured by the number of pounds, or kilogrammes, required to break a bar of given cross-section, usually a square inch or a square centimetre. When the weight is applied as a pull, we measure the tensile strength of the material. When applied as pressure, we measure the compression strength.

28. **Adhesion** is the general name given to the bond existing between unlike molecules—that is, between the molecules of different substances. When a glass rod is dipped into water, a thin film of the liquid spreads itself over the glass, and the attraction between the two is considerable. We can measure adhesion if we balance a pane of glass so that its under surface just touches the surface of the water, and then add weights until the glass is pulled away. In the same manner light articles, such as pieces of tissue paper, feathers, and the like, will stick to the hand and to one another.

29. **Elasticity.**—When a body has its form altered by either a pull or by pressure, the result is called a *strain*, and the pull or pressure itself is spoken of as the *stress.* If, when the stress is removed the strain also disappears, the body is said to be elastic. Such is the case with rubber, whalebone, and many other substances. If the strain always disappears when the stress is removed, no matter how great the stress may be, the body is said to be perfectly elastic. Fluids are the only bodies which fulfill this condition. No solids are perfectly elastic. The degree of their elasticity is measured by the coefficient of elasticity. This is the weight which would be required to stretch a bar of unit cross-section (such as one square centimetre) to twice its original length, were that possible, and still have the bar regain its original length when the stress is removed.

30. **Malleability.**—When the molecules of a body are so arranged, or so related to one another, that we may pound the body into thin sheets without breaking it, we describe the body as malleable. Gold is probably the most malleable of all substances. It has been beaten into leaves so thin that one hundred and twenty thousand were required to make a pile one centimetre high.

31. **Ductility** expresses the arrangement of molecules of a body which permits it to be drawn into small rods and wire. Platinum possesses this property in a marked degree.

The finest wires are obtained by coating a platinum wire with silver, then drawing it out as fine as possible, and dissolving off the silver by means of nitric acid.

Both malleability and ductility depend upon the possibility of rearranging the molecules of a body within such narrow limits that the bond between them—that is, their cohesion—will not be broken. This possibility depends upon several factors, such as temperature and purity of material. Even small quantities of arsenic or antimony will seriously interfere with the working of copper; and sulphur and phosphorus have a similar effect upon iron.*

32. **Viscosity and Brittleness.**—No substances, even among solids, are perfectly rigid. In all matter the molecules have more or less ability to change their relative positions, and consequently the body containing them to change its form. On the other hand, no substances, even among gases, are perfectly fluid. In all there is more or less retardation of motion due to an apparent friction among the molecules themselves.

This property of matter is called viscosity. In solids it makes permanence of form impossible. A straight glass rod, resting for some time upon two supports, gradually assumes a curved form under the stress of its own weight. An iron girder, between two piers, takes a permanent sag. A cane, standing in the corner, becomes crooked.

In fluids viscosity comes in as a constant retardation to motion. Streams do not at once seek their lowest levels, but take an appreciable time. Waves do not continue indefinitely, but finally spend themselves, overcome by the friction of the fluid itself, their motion turned into heat. Fine particles remain suspended in water and air for a long time, their weight being insufficient to overcome viscosity. Storms finally spend themselves.

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* See Chemistry.

When a stress acts upon a solid, either as pull or pressure, in such a way as to make this rearrangement of molecules impossible, the particles separate, and we call the body brittle.

33. **Diffusibility.**—We conceive that the molecules of all matter are in a constant state of motion. In consequence of this activity, two gases or two liquids capable of mixing, when placed in communication with each other, will become evenly distributed throughout the total volume. This *diffusion* can be shown by several simple experiments:

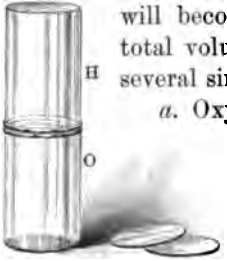

FIG. 4.—Diffusion of oxygen and hydrogen.

a. Oxygen is sixteen times as heavy as hydrogen. When brought together they form a highly explosive mixture. If an inverted jar of hydrogen be placed above a jar of oxygen, the glass cover plates withdrawn, and the two jars allowed to stand in communication for several hours, it will be found that, in spite of their differences in weight, the two gases have thoroughly diffused and each jar contains an explosive mixture. On separating the jars and applying a match, two almost equally loud reports are heard.

b. If clear water be carefully added to the top of a tumbler already partly filled with colored water, such as a solution of copper sulphate, and the whole allowed to stand for some time, it will be found that the color distributes itself almost equally throughout the tumbler.

This diffusion of fluids takes place even when the two are separated by a porous partition. In general, the lighter fluid passes through more quickly than the heavier, as may be shown by the following experiment:

c. An inverted porous cup, such as is used in the Daniell cell, has its lower end sealed by a tight rubber stopper, through which a long glass tube passes. The free end of the tube dips under the surface of a colored liquid in a tumbler below. If, now, a bell jar filled with hydrogen be quickly brought over the porous cup, the air inside the cup will be forced down the glass tube and will bubble through the colored liquid. The hydrogen makes its way through the porous cup faster than the heavier air can make its way out. When the bell jar is removed, the reverse takes place. The hydrogen inside the cup escapes faster than the air can take its place, a partial vacuum is produced, and the colored liquid rises in the tube.

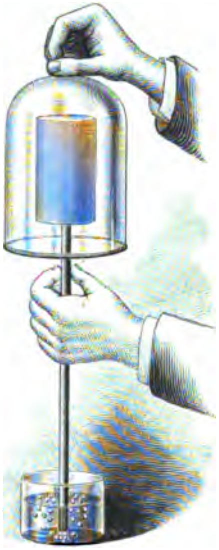

FIG. 5.—Diffusion of hydrogen through porous cup.

d. In the same way liquids diffuse into each other through unglazed earthenware, parchment paper, and other porous partitions. The action is known as *osmose.* Dissolved solids have the same power, provided they are crystallizable. Amorphous substances, or colloids, do not diffuse. Chemists sometimes make use of this difference of behavior to separate some crystallizable poison, such as arsenious acid, from the amorphous contents of the stomach of an animal supposed to have been poisoned. The process is known as *dialysis*, and is easily carried out in the apparatus (dialyzer) shown.

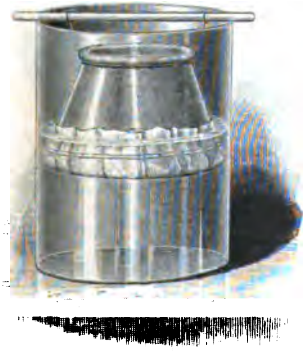

FIG. 6.—Dialyzer.

34. Capillarity.—If tubes of very small diameter are partly immersed in water or other liquid which wets them, it will be noticed that on withdrawing them in part the level of the liquid in the tubes is considerably above that outside, and is higher as the diameter of the tubes is smaller. In case of mercury or other liquid which does not wet the glass, there is a depression of level in the tubes in place of elevation.

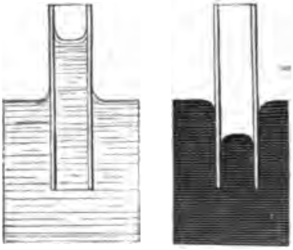

FIG. 7.—Capillary elevation and depression.

The same appearances may be seen when solids and liquids come into contact. The water in a tumbler rises around the edge, and the surface of the liquid is concave. Mercury, on the contrary, would be depressed around the edge of the tumbler, and would present a convex surface. Drops of mercury on a table take the form of globules. Water behaves in the same way if the table be greasy or dusty.

Since these elevations and depressions are most noticeable in hairlike or capillary tubes, the name *capillarity* has been applied to the phenomena. They appear to be strictly molecular phenomena, and to depend upon the relative strength of cohesion and adhesion. Where the cohesion within the liquid is stronger than the adhesion between the solid and liquid, the resulting strain shows itself as capillary depression; but where the adhesion between solid and liquid is the stronger, the strain is a capillary ascension.

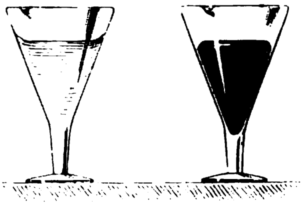

FIG. 8.—Capillary curves.

We find many illustrations of capillary action in Nature —such as the rising of oil in the wick of lamps; the curious efflorescence of salt over the edge of the tumbler when salt water evaporates; and the wetting of the whole towel when one corner is left in a basin of water.

EXPERIMENTS.—1. Try the hardness of such stone and building material as may be convenient—marble, brownstone, brick, etc.

2. Determine the hardness of pyrite, garnet, graphite, and any other common minerals that may be within reach.

3. Let the teacher or pupil, or both, repeat the experiments *a*, *b*, *c*, and *d* (33), and also those under capillarity (34).

CHAPTER IV

ON MEASUREMENT

APPARATUS: Yardstick, pound weight, quart measure. Metric units, metre, gramme, and litre. Metric chart. A good scale, weighing up to several pounds. English and metric weights.

35. **Science** is exact knowledge. This is only gained by comparison or measurement. "We have only so much science as we have mathematics." The first step, therefore, in the study of practical physics is to learn how to measure.

Measurement involves two processes:

1. The establishment of a standard or unit of measurement with which we can compare our unknown quantity.
2. The method by which we carry out this comparison.

36. **Units.**—The choice of standard units must naturally depend upon what we wish to measure, and our units must necessarily be as numerous as the qualities measured: one unit for length, as the yard; another for volume, as the gallon; another for weight, as the pound; and so on.

The objection to these common English units, however, is that they bear no easily expressed relation to one another, and consequently it is quite inconvenient [illegible] translate one unit into another—as cubic yards into gallons.

The best system of measurement [illegible] in which the different units are simply related, and are easily deducible the one from the other. The metric system [illegible] such a scheme of measurement, and is therefore always used in scientific work. In it the unit of mass depends upon the unit of volume, and this in turn upon the unit of length. When we establish the unit of length, therefore, we establish the others.

METRIC TABLES.

Length.

1 millimetre = .0393 inches.
1 centimetre = .3937 " = 10 millimetres.
1 decimetre = 3.9370 " = 10 centimetres.
1 metre = 39.37 " = 10 decimetres.
1 kilometre = .62137 miles = 1,000 metres.

1 inch = 2.54 centimetres.
1 foot = 30.48 "
1 yard = 91.44 "
1 mile = 1,609.33 metres.

Volume.

1 cubic decimetre = 1,000 cubic centimetres = 1 litre = 1.0567 quarts
1 quart = .9462 litres = 946.25 cubic centimetres.

Mass.

1 gram = 15.4323 grains.
1 kilogram = 1,000 grams = 2.2046 pounds (avoirdupois).

1 ounce (avoirdupois) = 28.349 grams.
1 pound " = 453.5926 "
1 ton " = 907.185 kilograms.

In physics we measure both matter and motion. Our series of standards, therefore, must be comprehensive enough to apply to all measurable aspects of matter and motion. By taking a series of related units it is not difficult to establish even so far-reaching a system as this, for we find practically that only three fundamental units are necessary. These are the unit of length, the unit of mass, and the unit of time. They form the basis of all physical measurement.

37. **Length.**—It is unnecessary to define length. We all understand by it the distance between two points, or their separation in space. The unit of length is the *centimetre*, the one hundredth part of the metre. It was originally intended that the metre should be the one forty millionth

part of the earth's meridian. Practically, it is the length of a standard platinum bar, copies of which are kept in the national archives at Washington, London, Paris, and Berlin.

Most of us are accustomed to thinking of length in inches. It may therefore help us to gain a clear idea of the centimetre if we remember that it is about four tenths of an inch. As soon as possible, however, it will be well to think of the centimetre as a unit in itself, and not to translate it into inches.

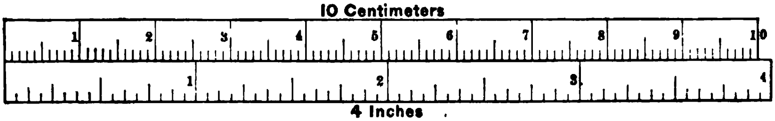

FIG. 9.—Comparison of centimetres and inches.

38. **Mass.**—The mass of a body is the amount of matter it contains. The unit of mass is the *gramme*. This was intended to be the mass of one cubic centimetre of pure distilled water at the temperature of greatest density. Practically, it is the one thousandth part of the standard platinum kilogramme, copies of which are also kept in the national archives of the several civilized nations. The kilogramme is about equivalent to two and one fifth pounds avoirdupois. The gramme equals .0352 ounces, and one ounce equals 28.35 grammes.

39. **Time.**—This can not well be defined, but we all know something of the meaning of the word. It is our name for the sequence of events. The unit of time is the *second*. It is the $\frac{1}{86400}$ part of an average day (mean solar day).

40. **The C.-G.-S. System.**—The system of measurement founded on these three fundamental units is known as the centimetre-gramme-second system, or, more briefly, as the C.-G.-S. system. The units depending on these fundamentals are called derived units, and are capable of expressing all measurable aspects of matter and motion.

41. **The Two Terms in Measurement.**—It is to be observed that every expression of physical magnitude requires two terms: One, the numerical term, or coefficient, and the other the verbal term, or name of the standard unit, as, for example, 10 centimetres, 8 grammes, 60 seconds. The verbal terms are either the fundamental or derived units we have been considering, and are agreed upon before beginning the measurement. This done, the real process of measurement consists in finding the coefficient, or the number of times the standard unit is contained in the unknown quantity to be measured.

42. **Methods of Measurement.**—The comparison between the standard unit and the quantity to be measured may be made directly or indirectly.

It is made directly when we apply our foot rule at once to the piece of timber to be measured, or when we pour water or other liquid into a gallon measure.

In general, however, our measurements are made indirectly, as when we find the area of a farm by measuring the length of its boundaries, or the temperature of a room by observing the length of a column of mercury in a thermometer.

Indeed, it seldom happens that quantities can be measured directly. In most cases we are forced to resort to indirect methods. It is in devising these that physicists show their skill and ingenuity.

The measurements most open to the direct method are those of length, but even here greater accuracy is often obtained by indirect methods, as when we find the diameter of a glass tube from the weight of the mercury which is required to fill a given length of the tube, or when we calculate the diameter of a wire from its length and weight.

43. **Mathematical Physics.**—We must then consider modern physics simply as an interesting branch of applied mathematics. It is a science of measurement, and can be studied to best advantage in the laboratory. Practical

laboratory work means simply measurement. In the following pages much of our time must be given to the double work of establishing a suitable system of derived units, and of applying these to the measurement of physical magnitudes. The student who goes to work in earnest should first see that he thoroughly understands the unit, and should then, as far as possible, make all the measurements for himself by which the coefficient that is to stand before the unit is determined. Where the facilities of the school do not permit the student to make these measurements for himself, he should at least see them made, and thoroughly participate in working out the subsequent determinations.

44. **Conservation of Matter.**—It is possible to measure matter and to reason about it only because of its persistence. The sum total of matter always remains the same. We can not create it; we can not destroy it. Our experience leads to the belief that its mass is absolutely constant. Nor can we even think of matter as coming out of nothingness, or passing into nothingness again. This all-important truth is known as the *conservation of matter*, and was only generally accepted at the close of the eighteenth century. We can not prove it by direct experiment, for every method would have to start out by assuming what we wanted to prove, but reason and general experience are ample proof.

45. **Conservation of Energy.**—In like manner it is only possible to measure and study motion because of its persistence. This is a less obvious truth than the conservation of matter, for we see on all sides the apparent destruction and creation of motion. But a more careful examination shows that the disappearance of motion is always followed by its reappearance in some other form or in some other body, while its seeming creation is in reality a similar transformation or transference. We therefore believe that the total amount of motion is constant—a truth which we define as the *conservation of energy*. It is only within the past half

century that this truth has been clearly established. It has made possible the science of modern physics.

46. **Rationality.**—We can not overestimate the importance of the recognition of these sister truths, the conservation of matter and the conservation of energy. If we lived in a world in which the amount of matter and motion was constantly changing, we should be unable to reason about them, or indeed about anything. We should be practically insane, for we should be unable to establish any relation between the events of life. All would be wild chance and caprice. This is much the position to-day of those persons who do not realize these fundamental truths. They live in a world of unreason and chaos. Judged in this way, but a small percentage of the inhabitants of the earth are rational. Civilization is only possible because human experience is uniform.

EXPERIMENTS.—1. Measure the four dimensions of a sheet of paper in millimetres, and express its area in square centimetres.

2. Measure the length of a rod ten times, take the average result, and express the greatest mean error.

3. Measure a regular-shaped block of wood in millimetres, and express its cubical contents in metres.

4. Measure the linear dimensions of the room you are in, and express its volume in litres.

5. Put a kilogramme weight on the scale, and find its equivalent in English measure.

6. Put a pound weight on the scale, and find its equivalent in grammes.

7. Weigh a quart of water in grammes, and calculate the length of tube, one centimetre in diameter, that this amount of water would fill.

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CHAPTER V

MEASUREMENT OF MATTER

APPARATUS: Spring compass. Calipers. Micrometer screw. Cathetometer. Measuring engine. Vernier. Surveyor's tape or chain. Transit. Graduated glass jar.

47. **The Problem.**—The exact measurement of matter is necessary in physics in order that matter may be accurately studied as a carrier of motion. The amount of motion we have in matter depends upon the amount of matter we have moving, as well as upon the rate at which it moves. For this purpose the measurements of matter with which physics has most to deal are those of extension—length, area, and volume—of mass and weight, of density and specific gravity.

48. **Extension in One Direction.**—The measurement of length is of the utmost importance in physical work, not only for itself, but also because so many other measurements depend directly upon it. The process involves no theory. It depends entirely upon the precision of the instruments of measurement, and the care with which they are employed. The simplest of these instruments is the divided scale. For scientific work, its unit is the centimetre and its subdivisions. In determining length, we must first make up our minds as to the degree of accuracy needed. In comparatively rough work, we apply the scale directly, and read off the result with the naked eye, as when we measure the length of a line on a drawing, or the length of a piece of wood or iron.

But this direct method involves two sources of error. We can not be sure that the initial division on the scale exactly coincides with the beginning of the line to be measured, nor can we accurately judge of the fractional subdivisions of the scale. To avoid one or other or both of these sources of error is the purpose of our instruments of precision. It is well to make one's self acquainted with several of the more important of these instruments.

The *spring compass*, used in every drawing-room, is simply a means of transferring a measurement, with great accuracy, from line to scale, or scale to line. Yet even so simple an instrument is only used accurately after some practice.

The *calipers* and *screw gauge* are much alike. Their arms or screw ends encompass the object to be measured, and when placed in close contact with it their distance apart is read off from the little scale attached to the movable arm.

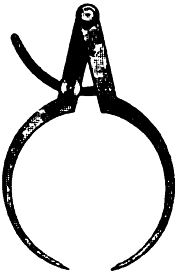


FIG. 10.—Calipers.

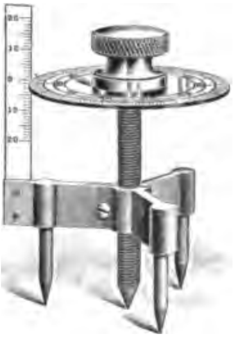


FIG. 11.—Micrometer screw.

The *micrometer screw* is used for determining the thickness of thin sheets of metal, paper, glass, and the like. It consists of a rigid frame of metal, supported by three fixed legs. A fourth leg, in the shape of a finely threaded screw, turns in a screw bearing in the center of the frame, and is provided with a large circular head, accurately divided, so that one may easily read the fraction of a turn made by the screw. If the head makes one complete turn, the leg moves through a distance equal to the screw thread, and for any smaller turn the motion is proportional.

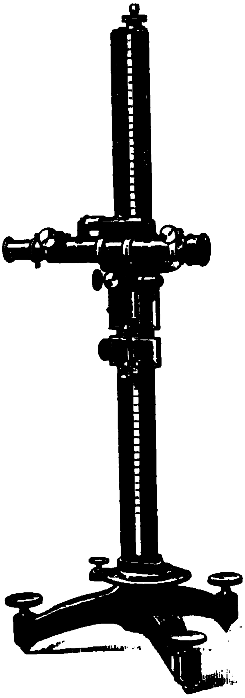


Fig. 12.—Cathetometer.

The micrometer screw may also be used as a *spherometer*, an instrument for finding the curvature of spherical surfaces.

The *cathetometer* measures accurately small vertical distances. It consists of a rigid upright scale, provided with a sliding telescope carrying a second smaller scale. A reading is taken when the cross-hairs of the telescope exactly coincide with one end of the distance to be measured, and a second reading when they coincide with the other end. The difference between these readings equals the distance.

The *vernier* is a device for helping the eye to read tiny subdivisions of a given scale. It is used on many instruments of precision. The principle is very simple. A definite length, say an inch or a centimetre, is divided into *ten* equal parts. A second length is taken, equal to *eleven* of these equal parts, and is itself divided into ten parts. If the two scales be laid alongside of each other, it is very evident that the subdivisions on the longer

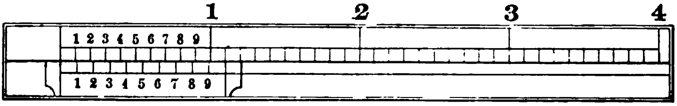


Fig. 13.—Vernier, set at zero.

scale will overlap those on the shorter scale by just one tenth, as shown in the diagram (Fig. 13). Suppose, now, that the initial marks on the two scales do not coincide, but that the shorter one is four tenths of a division ahead of the longer one, as shown in Fig. 14. We shall know the exact amount by observing that the subdivisions marked 4 on both scales now coincide, and this can only occur when the shorter scale is four tenths ahead.

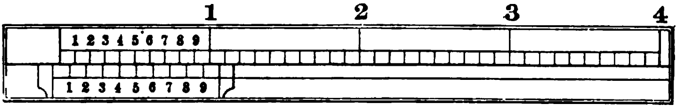


FIG. 14.—Vernier, reading four tenths.

49. **Surveying.**—The instruments already considered serve only to measure very short lengths, such as those met in the laboratory. In measuring greater lengths, as in surveying field, or farm, or State, enlarged methods have to be adopted. In ordinary farm or railroad work it is sufficiently accurate to measure distance by means of steel or linen tapes, or iron chains. These are generally one hundred feet long. They are divided into feet, and these again into tenths.

In the case of very large and accurate surveys, such as those made by the United States Coast Survey, generally only one length is measured, and the other distances are calculated from this. This one line is known as the *base line*, and is measured as accurately as possible. It is sometimes several miles long. The ground is cleared and leveled as carefully as if a road were being constructed. The length is found by means of rigid measuring rods placed end to end, and the contact observed by means of telescopes.

50. **Extension in Two Directions.**—We seldom or never measure area directly; that is, by applying the unit of area, the square centimetre, to the surface to be measured. In nearly all cases we measure the linear dimensions and cal-

culate the area from these by means of the simpler propositions in plane geometry. Thus, for example, to get the area of a rectangle, we measure the base and altitude. Their product equals the area. To find the area of a triangle we make the same measurements, knowing that half the product will be the area. And similarly with other surfaces.

51. **Extension in Three Directions.**—If the volume to be measured is regular in outline, we measure the linear dimensions and calculate the volume from these by means of the propositions of solid geometry. But if the solid be irregular in shape, as is generally the case, we can best find its volume by immersing it in water or other fluid and determining the volume of the fluid displaced.

Example.—The volume of an irregularly shaped stone can readily be found by suspending it in a graduated jar of water. The rise of water in the jar will indicate the cubical contents of the stone. Or, the jar may be completely filled with water, the stone carefully lowered into it, and the overflow of water caught in a measuring glass, as shown in figure.

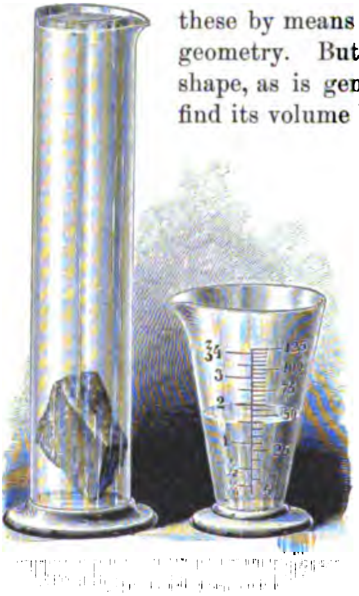


FIG. 15.—Measuring the volume of a stone.

The volume of fluids is obtained by measuring the dimensions of the containing vessel, and then calculating its contents. In case the vessel is irregular in form, we can find its volume by filling it with some liquid, such as mercury, weighing the mercury, and then calculating the volume by means of the known relation between the weight and volume of the mercury (see Chapter VII).

As every cubic centimetre of mercury weighs 13.56 grammes, we have only to divide the weight of the mercury in grammes by 13.56 to get the volume of the vessel in cubic centimetres.

EXPERIMENTS.—1. Make two dots some distance apart on a sheet of paper. Measure the distance five times by direct application of the divided scale; take the mean, and see if this corresponds to one measurement made by the spring compass.

2. Determine the thickness of a glass cover plate by means of the micrometer screw.

3. Determine the thickness of a visiting card by the same instrument.

4. Measure the diameter of a nickel five-cent piece by the calipers.

5. Construct a vernier in stiff paper, making the vernier $\frac{1}{10}$ of a subdivision on a fixed scale. Do the same, making the vernier $\frac{2}{10}$ of a subdivision.

6. Determine the area of a lot or small field.

7. Find the volume of an irregular-shaped stone or mineral by immersing it in water, and measuring the water displaced.

8. Find the volume of a small test tube by weighing the mercury required to fill it.

Note.—Can you from this weight, and the known length of the test tube, calculate its diameter?

REFERENCE.

Gillespie's Surveying, or any other standard work.

The Coast Survey in Harper's Monthly for March, 1879, vol. lviii, p. 506.

CHAPTER VI

MASS AND WEIGHT

Apparatus: Cubes of the same size, but made out of different material, such as cork, wood, clay, metal. A scientific balance, with weights from .001 to 50. grammes.

52. **Mass.**—We have defined mass as the quantity of matter in a body. The unit by which it is measured is the gramme.

If we have two spheres of different size but made of the same material, the larger one will of course contain the greater mass. In case, however, the material is different, the smaller sphere may have the greater mass. We say, then, that mass is independent of volume, and we can not judge of the mass of a body by simply looking at it, or even by measuring its dimensions.

Suppose, for example, we have half a dozen cubes, made of cork, wood, marble, iron, silver, and gold, respectively, and each one centimetre in dimension. Their volumes, being equal, would be represented by the proportion:

$$1 : 1 : 1 : 1 : 1 : 1,$$

while their masses would be found on experiment to be represented very closely by the proportion:

$$1 : 3 : 11 : 30 : 42 : 76.$$

That is to say, a cube of gold has seventy-six times the amount of matter contained in a cube of cork of the same size. But while we can not perceive these differences in mass by the eye, we do perceive them very readily on handling the cubes. The greater the mass, the more effort it takes to move or lift them. This is our common method of judging of the mass of bodies—that is, by what we call their *weight.*

In general, the weight of a body is directly proportional to its mass, but we must be very careful in physics not to confound the two terms. The mass of a body is a constant quantity no matter where the body may be placed; while the weight is a variable quantity depending upon circumstances. Mass and Weight are therefore two entirely distinct expressions, and must never be used the one for the other. The reason for this will appear still clearer on considering what we mean by weight.

53. **Gravitation.**—As far as human experience extends, it is found that all bodies in the universe tend to move toward one another. We call this tendency *gravitation.* Its intensity depends upon two factors—the quantity of matter, and the intervening space, or distance. The gravitation between two bodies is greater the larger their mass and the smaller their distance apart. This was first stated by Newton, somewhat as follows:

"Every particle of matter in the universe tends to move toward every other particle in a straight line joining the two, and with an intensity depending directly upon the product of their masses and inversely upon the square of their distance apart."

We have no explanation of gravitation. We do not know why bodies tend to move toward one another, and we never expect to know. The above statement simply expresses the observed fact. The name gravitation gives us a convenient term by which to refer to the action, but it does not explain it.

54. **The Formula of Gravitation.**—It is often convenient to sum up our observations in a mathematical expression or formula. This is simply an exact and short-hand way of representing observed facts. Nearly all young students strongly object to formulas, under the mistaken belief that

they are difficult and obscure. On the contrary, they are easy and clear. No great progress can be made in so exact a science as physics without their use, and it would be well for every student at the very outset to make up his mind to understand and use them. This particularly applies to gravitation, where we sum up the whole matter very briefly as follows:

$$G = \frac{m\,m'}{d^2}$$

in which G stands for gravitation, m and m' for the masses of two bodies, and d for their distance apart. It should perhaps be added that the distance is measured from the center of mass, which is commonly spoken of as the center of gravity. In case the body is homogeneous—that is, of the same constitution throughout—the center of mass corresponds to the center of figure.

55. **Weight.**—In harmony with this universal principle of gravitation, all bodies at the surface of the earth tend to move toward its center of mass with an intensity depending upon their mass and inversely upon the square of their distance from the center.

56. **Weight as the Measure of Gravitation.**—We can now understand why weight is a variable quantity, and we can understand it still better if we repeat our formula of gravitation:

$$G = \frac{m\,m'}{d^2}$$

In this fraction, m', the mass of the earth, and m, the mass of the body weighed, are constant, while d, the distance from the center of the earth, is constant for any one place, but differs for different places. Therefore the weight, depending as it does upon G, depends inversely upon d^2, and will differ in different places.

As we pass from the equator to the poles we come thirteen miles nearer to the center of the earth, and therefore the weight of bodies increases.

As we ascend high mountains we pass one, two, three, four, sometimes over five miles farther from the earth, and therefore the weight decreases.

We may even imagine conditions such that weight would disappear entirely. There is a point between the earth and the moon where the gravitation toward one body is just equal and opposite to that toward the other. A particle at that point would practically have no weight.

But meanwhile the mass has undergone no change. At the equator, at the pole, on the high mountain, out in space, the quantity of matter was the same.

We may therefore say that mass is independent of weight as well as of volume.

57. **Measurement of Mass.**—We can not measure mass directly, since we can not directly compare our standard gramme with the unknown mass to be measured.

We must therefore measure mass indirectly—that is, by some general effect of mass common to all forms of matter.

Weight is the most convenient measure of mass, and the one commonly employed, since weight, as we have just seen, is directly dependent upon mass, and is constant for any given place on the earth's surface. The practical operation of finding the mass of a body consists therefore in the process of weighing.

58. **Weighing.**—The operation of weighing is carried out by means of very delicate balances and very carefully standardized weights. It is best learned by practice. It is always necessary to test such sensitive instruments before using them, as they are very liable to get out of adjustment. The weights also must be examined from time to time and compared with standard weights.

Two methods are in use—direct weighing and counterpoise weighing.

In the first, the object to be weighed is put in one scale pan and the weights in the other. Where the balance is accurate, it is the more convenient and better method.

In the second method the object to be weighed is put in one scale pan, and fine shot or sand added to the other, until the pointer is at zero. The object is then removed, and weights put on the scale pan in its place until the balance is again even. This method neutralizes any inaccuracy in the balance itself.

The balance commonly used in physical work will weigh from several hundred grammes down to the tenth of a milligramme. The weights of one gramme and over are made of brass. Those less than a gramme and down to ten milligrammes are made of platinum, while the milligramme weights are made of aluminium, in order that they may have greater volume and consequently be easier to handle. The fractions of a milligramme are measured by a small platinum rider which is placed on the arm of the balance. The farther it is moved from the point of support the larger value it has.

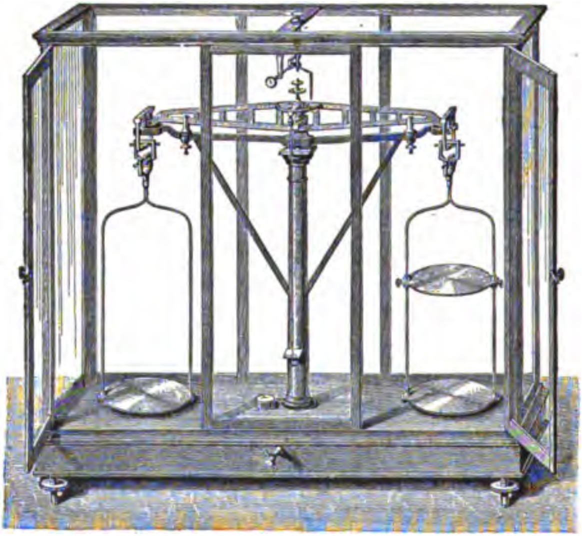


FIG. 16.—Balance for accurate weighing.

When the right weight has been found, and the pointer stands at zero, the results should be entered in a notebook before the weights themselves are disturbed. This saves many mistakes. It is well to take the reading by noting what weights are absent from the box, and then verify the result when the weights are put back in place.

Experiments.—1. Weigh any convenient object first directly and then by counterpoising, and compare the results.

2. Weigh the same object with an added fifty-gramme weight on each scale pan, and see if the balance is equally sensitive.

3. Find the least mass that may be accurately weighed on your balance, and see if it is the same when the scale pans are each loaded with one-hundred-gramme weights.

Problems.—1. If an object could be carried to the center of the earth, what would be its weight?

2. In going toward the center of the earth, weight at first increases and afterward diminishes. Why?

3. Would a man weigh, more or less, on the moon than on the earth?

Reference.

Chapters on the Balance and on Weighing, in Practical Physics: Glazebrook and Shaw.

Other Worlds than Ours, by Richard A. Proctor.

CHAPTER VII

DENSITY AND SPECIFIC GRAVITY

APPARATUS: Hydrostatic balance and weights. Distilled water. Eight-ounce beakers. Plunger. Specific-gravity bottle of fifty cubic centimetres' capacity. Hydrometers. Alcoholometer. Lactometer.

59. **Density.**—We speak of bodies as being light or heavy, and by this we mean light or heavy in proportion to their size. A small cube of gold contains comparatively a large amount of matter, and we speak of gold as being very heavy. A similar cube of cork contains little matter, and we speak of cork as being very light. This relation between mass and volume is known in physics as *density*. Since mass is measured by weight, we may define density practically as the weight of a unit of volume of the substance. The unit of volume being the cubic centimetre, and the unit of mass the gramme, we express the density of a substance when we state the number of grammes contained in one cubic centimetre of the substance.

The following table gives the density of a number of common substances:

TABLE OF DENSITIES.

Cork	0.240
Wood	0.434 to 1.330
Ice	0.917 " 0.918
Wax	0.960
Human body	0.987
Coal	1.300 to 1.500
Sand	1.420
Clay	1.900

TABLE OF DENSITIES (*continued*).

Retort carbon	1.90
Graphite	2.17 to 2.33
Crown glass	2.52
Marble	2.65
Quartz	2.65
Flint glass	3.00 to 6.00
Diamond	3.49 " 3.53
Cast iron	7.00 " 7.70
Wrought iron	7.80 " 7.85
Bronze (Cu and Sn)	8.70 " 8.90
German silver (Cu, Zn, and Ni)	8.30 " 8.40
Brass (Cu and Zn)	8.20 " 8.70

Water	1.00000
Ether	0.74000
Alcohol	0.80620
Turpentine	0.97000
Olive oil	0.91000
Sea water	1.02600
Milk	1.03200

Air	0.001293
Carbonic-acid gas	0.001939

NOTE.—For specific gravity of single metals and other elements, see Table of Elements, pp. 12–14.

It is to be observed that density varies under different conditions. We may increase density by packing the molecules of a body closer together, as when we roll or hammer metals or compress gases. We may diminish density by allowing the molecules to separate, as when we expand bodies by heat. Hence it is that in stating the density of gases we must mention the temperature and also the pressure to which they are subjected; and of solids, the temperature and the mode of preparation.

60. **Specific Gravity** is an expression somewhat similar to density and yet not quite identical with it. Specific gravity bears much the same relation to density that weight does

to mass. It is our practical measure of the relation between weight and volume.

Specific gravity may be defined as the ratio between the weight of a given volume of the substance and the weight of the same volume of a second substance taken as a standard.

This is the same as saying that it is the ratio between the density of the substance and the density of the standard substance.

The specific gravity of solids and liquids is referred to water as a standard. Since the density of water is 1, the same numbers express both the density and specific gravity of solids and liquids.

The specific gravity of gases is referred to air as a standard, but since the density of air is only .001293, the numbers expressing the density and specific gravity of gases are far from being the same.

We shall have nothing to say in this work about methods of finding the specific gravity of gases. It will be interesting to note, however, what is the specific gravity of a few of the more familiar ones, as follows:

Air	1.000	Carbon monoxide	0.967
Hydrogen	0.069	Carbon dioxide	1.529
Oxygen	1.106	Hydrogen sulphide	1.191
Nitrogen	0.971	Hydrochloric acid	1.254
Ammonia	0.537	Sulphur dioxide	2.247
Chlorine	3.440	Marsh gas	0.559

The determination of the specific gravity of solids and liquids is an operation of much importance. It is commonly carried out by one of the following methods:

1. The hydrostatic balance.
2. The specific-gravity bottle.
3. The hydrometer.

The second method only will be considered here, the first and third being deferred until after buoyancy has been treated.

61. **Specific-Gravity Bottle.**—This is a small glass flask of known capacity, usually 50 cubic centimetres, or 50 grammes of water. The stopper is accurately ground, so as to fit correctly into the neck of the flask, and has a fine capillary bore, as shown in the figure, through which the excess of liquid may escape when the stopper is pressed into its seat. A brass counterpoise is provided which will just balance the flask and stopper. The whole purpose of the bottle is to provide a means by which we can always measure off precisely the same volume of a liquid. It must be used in connection with an accurate balance. The method applies to both solids and liquids.

a. Solids. — In this case the solid must be in small pieces, or in powder, so that it can readily be put into the bottle. A given weight is taken, generally about five grammes. The bottle is then carefully filled with distilled water and the stopper put in place, the excess of water escaping through the capillary tube. The whole bottle is now thoroughly dried with tissue paper and weighed. The specific gravity of the solid can easily be calculated. Suppose that just five grammes have been taken, and that the bottle has a capacity of just 50 grammes of distilled water at the ordinary temperature of the room. When the solid is in the bottle, however, the capacity is no longer 50 grammes of water, but is 50 grammes *less* the weight of the water displaced by the solid. Representing this by m, we

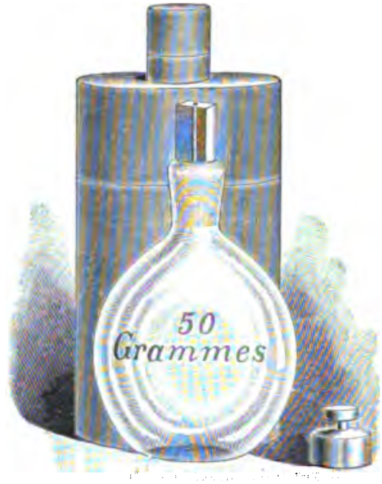


FIG. 17.—Specific-gravity bottle.

shall have $50 + 5 - m = \text{weight found} = w,$

or $m = 50 + 5 - w = 55 - w,$

and specific gravity $= \dfrac{\text{weight in air}}{\text{weight of equal volume of water}}$

$$= \frac{5}{m} = \frac{5}{55 - w}.$$

It is not necessary that the flask should hold just 50 grammes, or that we should take just 5 grammes of the solid. Indeed, in many cases it is much more convenient that we should not do so. If, for instance, we are determining the specific gravity of fine wire, and have cut it up into short lengths, it will be rather difficult to weigh out an even 5 grammes.

Example.—Silver wire.

Weight of silver taken	4.984 grammes.
Weight of water in flask	50.168 "
Weight of silver and water above it in flask	54.679 (w)
Weight of water displaced by silver $= 50.168 + 4.984 - 54.679 =$	.473 grammes (m).

$$\text{Specific gravity of silver} = \frac{4.984}{.473} = 10.52.$$

b. Liquids.—The specific-gravity bottle is especially adapted for the determination of the specific gravity of liquids. The whole process consists in filling the bottle carefully with the liquid to be determined, drying it as before with tissue paper, and weighing it. This weight (omitting, of course, the counterpoise) divided by the weight when filled with water, gives the specific gravity.

Example.—Milk.

Weight of water in flask	50.00 grammes.
Weight of milk in flask	51.60 "

$$\text{Specific gravity of milk} = \frac{51.6}{50} = 1.032.$$

CHAPTER VIII

MEASUREMENT OF MOTION

62. **Motion,** we have seen, is a change of position. To study and measure motion we must inquire what elements in it are variable. Now, motion is only manifested in bodies. We will not, therefore, study motion in the abstract, but we will study moving bodies. To do this completely we shall have to consider:

1. The space passed over.
2. The mass of the moving body.
3. The time.
4. The nature of the motion, whether uniform or variable.
5. The path of the moving body.

The *space* is simply the length of the path covered by the moving body. Where the path is straight—that is, where the motion is in a straight line—the space passed over is simply the length of a straight line joining the original position of the body and its final position. Where the path is a broken or curved line, the space passed over is the length of this line. In all cases we shall measure the space in centimetres, and designate it by s.

The *mass* of the moving body is usually expressed in grammes and represented by m.

The *time* is the number of seconds the body is in motion, and is represented by t.

These three quantities, s, m, and t, are all directly measurable by tape-line, balance, and clock. They are the three fundamental units of measurement in the C.-G.-S. system (41). There are relations between s and t, and between these two and m, that are highly important. They are defined as *velocity* and as *momentum.*

63. **Velocity.**—If a body move over a space of 50 metres, the final result is the same whether the motion takes place in a minute or in an hour. But we have not fully described the motion unless we have told the time it occupies. This rate of motion, or speed, is called *velocity* and is represented by v. We may define velocity as the space passed over by a moving body in one second of time. If the body be moving uniformly, or if we understand v to represent *average* velocity, we shall have

$$v = \frac{s}{t}.$$

64. **Momentum.**—It evidently makes a great difference whether the moving body is heavy or light, as we should find out very quickly if it struck us. A heavy body has more motion in it than a light body, even though both move at the same velocity. We define the amount of motion as *momentum*, and represent it by M. It is the product of the mass by the velocity:

$$M = mv.$$

A heavy body moving with little velocity may still have a much greater momentum than a light body moving with high velocity, but the effect of the two upon us will be very different. The heavy, slowly moving body will do us no harm if we, too, are free to move, because by a very slight effort we can give ourselves the same velocity as the body. But in the case of the light, rapidly moving body, say a bullet, the injury may readily be fatal. Before the bullet can be robbed of its momentum, it may penetrate to some vital spot. The velocity is so great that we can not hope to acquire it ourselves, and so repulse the bullet by going along with it.

65. **Nature of the Motion.**—Further, motion varies with respect to time—that is, is uniform or variable. Motion is *uniform* when the moving body passes over the same space each second. Motion is *variable* when the spaces passed over in successive seconds are different.

Acceleration.—This change of motion may itself be uniform or variable. It is uniform when the increase in the space passed over in successive seconds—that is, the increase of velocity—is the same. In this case, the uniform velocity added is called the *acceleration*. It is usually represented by a. If a body start from a state of rest, and add a velocity of a centimetres each second, it is manifest that its velocity at the end of t seconds will be equal to $t \times a$, or

$$V = at.$$

If a ball rolling down an inclined plane has at the end of each second respectively a velocity of 2, 4, 6, etc., the average velocity, or the space passed over in each second, will be, for the first second, the mean between 0 and 2 or 1, and for the others 3, 5, etc., the mean between 2 and 4, 4 and 6, etc.

66. **Path of a Moving Body.**—A moving body may trace any path whatever. The simplest path is, of course, a straight line. A boat moving without vibration over the surface of still water may trace an almost perfectly straight line. But the actual path of bodies is usually very much more complex than this. The path of the moon is an example. The moon moves around the earth in a constantly shifting path. She also moves with the earth around the sun. Further, she is probably, along with the sun and the rest of the solar system, making a grand tour through space around some other center. The actual path of the moon must be considered as compounded of these three and many other separate motions.

Curvilinear Path.—A body moving in a straight line would go on moving in a straight line forever, unless some second motion were compounded with the first, and so changed the path. We conceive that every curvilinear path is the result of compounding two or more motions. The most familiar example is that of a projectile of any kind thrown into space. Suppose it to be a ball and to be thrown horizontally. As we all know, it will approach nearer and nearer to the earth, and will finally strike. We explain this curvilinear path by saying that the ball has two motions: one in a horizontal direction, given by the throw; and another in a vertical direction, due to the weight of the ball —that is, to gravitation. We may represent this graphically by the diagram shown in Fig. 20, and this is a very convenient way of studying such curvilinear paths. In the

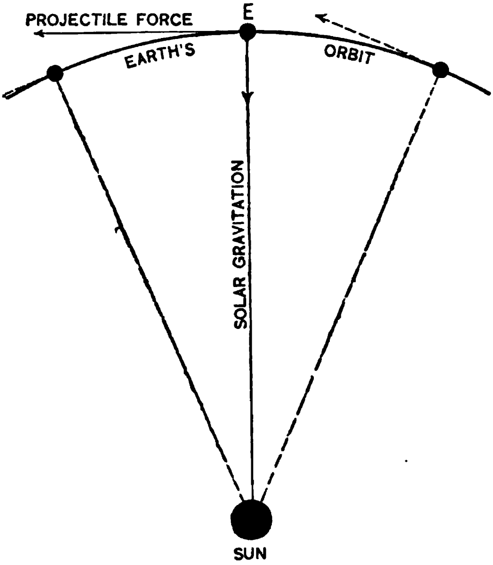


FIG. 18.—Motion of earth (*E*) around the sun.

case of all projectiles the path is a parabola, the curve produced when we pass a plane through a cone parallel to one of the elements of the cone; that is, to one of the lines joining the apex of the cone with some point on the base, and lying in the surface of the cone.

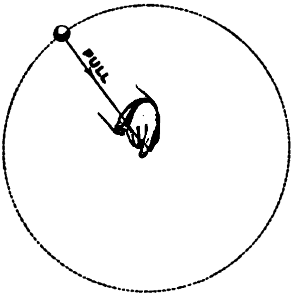


FIG. 19.—Motion of ball on end of a string.

In the same way the earth may be conceived as having two separate motions: one, its original projectile motion, if we may use such an expression; and the other its motion of constantly falling toward the sun. By the compounding of these two motions, we get a curve, which repeats itself each year, and is known as the path or orbit of the earth. This is an ellipse, the curve produced when a cone is cut by an oblique plane meeting all the elements (Fig. 18).

Similarly a ball or other heavy object attached to the end of a string may be twirled around so as to describe a circular path. Here the motion of the ball is constantly compounded with the pull exerted by the string. The ball, being kept at constant distance (the length of the string) from a fixed point (your hand), is forced to describe a circle, since a circle is the locus of all points in a plane at a fixed distance from a given point (Fig. 19).

These three paths—circle, ellipse, and parabola—are all comparatively simple, but they represent only a few out of many possible paths. The study of more complex paths requires a somewhat full mathematical knowledge, and will be found in larger works on mechanics.

Rotating Bodies.—We have so far assumed that the bodies we have been studying were moving freely in space. A special case of great practical importance is presented when one point of the body is fixed, and the only possible motion is one of rotation, as, for example, a carriage wheel or the fly-wheel of a steam engine. Here a series of points is fixed, what we call the axis of the wheel, and rotation takes place about this straight line. We can not speak of the velocity of such a rotating body, since all particles at different distances from the axis move with different velocities. The usual method of measuring such motion is to state the number of rotations per minute. A good average dynamo may make 1,200 rotations per minute.

67. **Units of Motion.**—We can evidently measure these several aspects of motion in the C.-G.-S. system.

Unit velocity is a velocity of 1 centimetre per second.

Unit momentum is a mass of 1 gramme moving with unit velocity—that is, 1 gramme moving 1 centimetre per second.

Unit acceleration is unit velocity added or subtracted each second—that is, 1 centimetre per second, each second.

Unit force ($F = ma$) is a change of unit momentum per second, or a change per second of 1 gramme moving 1 centimetre per second. This unit is known as the *dyne*, and is of great importance among physical units. It is commonly defined as that force which, acting for one second on 1 gramme of matter, imparts to it an acceleration of 1 centimetre per second.

PROBLEMS.—1. What is the velocity in centimetres per second of a boy riding a bicycle at the rate of twelve miles an hour? If the road be level and straight, what is his path?

2. What is the average velocity of an ocean steamer which requires six days to run from New York to Liverpool? Express in centimetres per second.

3. Assuming the boy to weigh 120 pounds, and the steamer 10,000 tons, compare the momentum of the two bodies.

4. What is the acceleration of a body which starts from a state of rest, and after moving for five seconds has a velocity of 160 feet per second? If, at the end of the five seconds, the same acceleration, but negative, acted on the body, when would it come to rest?

5. A stone attached to the end of a string is twirled around the hand. If the string break, what path will the stone describe?

6. The fly-wheel of a large pumping engine is making 120 rotations per minute. If the wheel be twelve feet in diameter, what will be the velocity, in centimetres per second, of any point on the circumference ?

7. If the body in problem 4 weighed ten grammes, what force in dynes was acting upon it ?

8. Why does a man running down a beach into the water invariably pitch head foremost ?

9. What path does the rash man describe who jumps from a moving street car ?

Reference.

Elements of Mechanics, by Oliver J. Lodge.

CHAPTER IX

FALLING BODIES

68. **Gravitation** (53–56).—All bodies near the surface of the earth will, if unsupported, fall toward the surface of the earth, or if supported will exert a pressure on the support equal to their weight. The term gravitation includes both the direct motion of falling bodies and the pressure or weight exerted by bodies at rest. We have already, in Chapter VI, considered gravitation as weight; it remains for us to consider it as motion.

Even Sir Isaac Newton, who investigated gravitation with a scientific thoroughness that has left little for subsequent inquirers to find out, declined to assign any cause for gravitation, and seems to have believed that it is beyond human ken to discover the cause. He was very explicit, however, in stating that action at a distance between two bodies is unthinkable—that is, he believed that two bodies in space can not attract each other across a perfect vacuum, and that no one with a philosophical mind would ever think such a thing. Our inability to conceive attraction between two totally unconnected bodies—that is, our inability to explain action at a distance—has made it necessary to fill all space with some medium which might serve as a common carrier for gravitation and all forms of radiant energy; that is, all forms of energy which, like radiant heat and light, travel through space in straight lines. This medium, the *Ether*, is supposed to fill all free space and also the intermolecular regions of all gases, liquids, and solids.

There is not a single physical fact which bears direct testimony to the existence of the ether, but nevertheless it is coming to figure more and more prominently in all physical discussions, because it enables us to deal with undoubted physical facts which we should otherwise be unable to handle. The present tendency is to regard gravitation as a strain in the ether by which bodies are *pushed* together, rather than as a mutual *pull* exerted by the bodies themselves.

The cause of gravitation has naturally aroused the curiosity of all thinking minds, but most men, like Newton, have put it aside as unknowable. Still, if you go to any great scientific library, you will find a few slender volumes which venture to discuss the problem.

69. **The Value of** g.—Every one knows that the farther a body falls the faster it goes. We do not hestitate to jump from the top of a fence, but no one is so foolish as to jump from a third-story window. Gravitation as motion—that is, the actual velocity—is not uniform, but is found by experiment to increase uniformly in all falling bodies. We therefore speak of gravitation as an acceleration (68), and since it is a special and very important acceleration, we represent it by a special symbol, g. This is the velocity added to a falling body each successive second.

g is not a constant; at the equator, at sea level, the value of g is 978.1 centimetres; at the poles, at sea level, it is 983.1 centimetres. This is partly due to the fact that at the poles one is about 21½ kilometres nearer to the center of the earth, and partly due to the fact that at the equator the earth's rotation tends to diminish g. If the earth turned seventeen times as fast as it does now, g would become zero; if faster than this, objects at the equator would be thrown off into space; g also varies with the altitude, being greater at sea level, and less on top of mountains.

The value of g for all places near the fortieth parallel of latitude may be taken as 980 centimetres (about 32 feet).

It is the same for all bodies, light or heavy, and only appears different on account of the unequal resistance offered by the air. In a vacuum all bodies fall with the same speed.

70. **Falling Bodies.**—The *velocity* of a falling body depends directly upon the length of time it has been falling. Since the acceleration g is added each second, the velocity at the end of t seconds must be t times g.

$$v = gt.$$

Taking g as 32 feet, we should have:

Velocity at end of 1st second = 32 feet.
" " " " 2d " = 64 "
" " " " 3d " = 96 "
" " " " 4th " = 128 "
" " " " 5th " = 160 "

The *space* passed over by a falling body is evidently the average velocity, multiplied by the time. The body, starting from rest, has an initial velocity of zero, and at the end of t seconds a final velocity of gt, and the average velocity will be the mean of these two:

$$v = \frac{o + gt}{2} = \tfrac{1}{2}\,gt.$$

Hence

$$s = \tfrac{1}{2}\,gt \times t = \tfrac{1}{2}\,gt^2.$$

This gives the *total space* passed over in t seconds. The spaces passed over in *successive seconds* are as follows:

During the 1st second = 16 feet.
" " 2d " = 48 "
" " 3d " = 80 "
" " 4th " = 112 "
" " 5th " = 144 "
350

The formulas give us a ready means of calculating all the elements involved in falling bodies.

71. **Projectiles.**—We have seen (69) that the motion of a projectile is compounded of two motions, the original projectile motion and the vertical motion of gravity. If we suppose a cannon ball to be fired horizontally from the top of a tower, its path would be represented as follows:

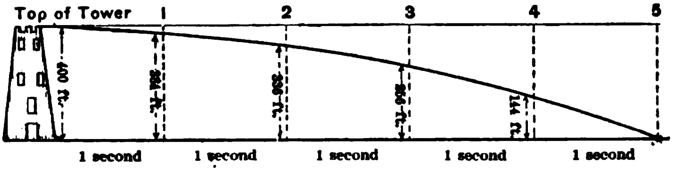


Fig. 20.—Path of a cannon ball.

If the tower were 400 feet high, the cannon ball would reach the earth in just 5 seconds. Had it simply been dropped from the top of the tower, it would have reached the earth in precisely the same time. This seems curious and at first sight impossible; but a moment's reflection will make the matter clear. In succeeding seconds the ball drops 16, 48, 80, 112, and 144 feet respectively, and this whether it is moving horizontally or not; hence in 5 seconds the ball must strike the earth. In practice, therefore, the cannon must be aimed at a considerable angle above the horizontal in order that the ball may carry any great distance. It is in this way that modern guns are able to throw a ball 13 miles and over.

72. **Suggestion.**—In the preceding paragraph the curvature of the earth was neglected. The surface was assumed to be plane. But, as we know, the surface is spherical, and in long-distance surveying this fact must always be taken into consideration. If, therefore, we could fire a cannon ball with sufficient speed to have the curvature of the earth just neutralize the fall due to gravity, and *if* there were no loss of speed by reason of the resistance of the air, and no interruption from mountains or other obstacles, our cannon ball would pass completely around the earth, and would become a satellite of the earth.

What speed would we have to give the cannon ball? In 1 second the ball falls 16 feet. To be at the same distance above the earth as when it started, the ball must in 1 second have reached a point where the curved surface of the earth is 16 feet below the horizontal line drawn through the starting place. This is the case at places five miles apart. Hence, our cannon ball to become a satellite of the earth would require a velocity of 5 miles a second—that is, 26,400 feet per second—and would pass around the earth in 1 hour, 23 minutes, and 20 seconds.

73. **Vertical Projectiles.**—If a body is thrown straight up in the air, its velocity becomes constantly less until finally the body comes to rest. Neglecting the resistance of the air, it is easy to calculate just how far up the body will go. Suppose its initial velocity to be 160 feet per second. Then, knowing that gravitation will rob it of 32 feet each second, we can readily see that at the end of 5 seconds the original impulse will be completely neutralized, and the body will momentarily come to rest. It is now 400 feet up in the air ($s = \frac{1}{2} gt^2$), and starts immediately to fall back toward the earth. The return journey also takes 5 seconds, and the final velocity will be the same as the initial velocity —160 feet per second. The entire excursion requires 10 seconds, and the velocity at any point is always the same, whether the body be going up or down.

PROBLEMS.—1. With what velocity would a man strike the water in falling from a bridge 150 feet high?

2. How far would a body fall in 10 seconds?

3. Through what distance does a body fall during the sixth second?

4. A stone is thrown upward with a velocity of 128 feet per second; what velocity has it when 192 feet high?

CHAPTER X

THE PENDULUM

74. **Importance of Pendulum.**—We shall devote a whole chapter, though a short one, to the pendulum alone, because of its importance in the study of motion and of gravity and its application in time-keeping.

We can best study the pendulum by means of an ideal instrument known as the simple pendulum. While this is purely imaginary, the results obtained from such a study may easily be applied to the real instrument by the addition of a few inconveniences.

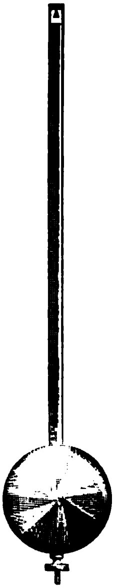


FIG. 21.—The pendulum.

75. **The Simple Pendulum.**—This consists of a heavy metallic bob, *M*, so homogeneous throughout as to have its centre of figure and centre of gravity at the same point. We conceive the entire mass to act as if concentrated at this point. The bob is suspended from the point of support, *O*, by a rigid thread which has neither weight nor friction. The length of a simple pendulum (l) is the distance, *O M*, from the point of support to the centre of gravity of the bob. (See Fig. 22.)

Ordinarily the pendulum will hang in a vertical line, *O M*. If *M* is displaced through the angle α to the position *M′*, it will tend to return to its original position by virtue of its weight. But when it reaches *M* it has acquired a certain momentum which carries it to the extreme position on the left, *M″*. If it were not for the resistance of the air (we have assumed the absence of friction) *MM″* would just equal *MM′*, and the pendulum would go on oscillating forever. As it is, the arc of displacement becomes gradually less, and the pendulum finally comes to rest again at *M*.

76. **The Motion of the Pendulum.**—When displaced, the return of the pendulum to the vertical is due not to the whole force of gravitation evidently, since the bob is suspended from *O* and can only move in an arc of a circle whose centre is at *O*. It must be due to some component of gravitation acting along the arc *MM′*. Let us investigate the matter. Gravitation can only act vertically downward, hence we must always represent it by a downward vertical line, as *M′a*. This may be resolved into two components, one (*M′d*) in the direction of the thread produced, and the other (*M′b*) at right angles to this, and consequently

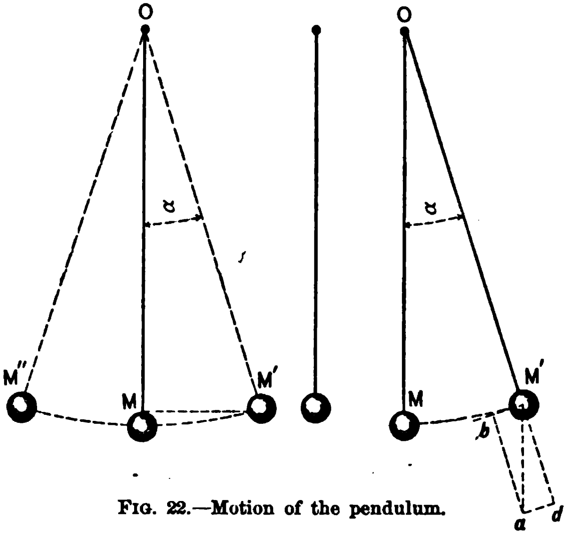


FIG. 22.—Motion of the pendulum.

tangent to $M'M$ at M'. The component $M'd$ represents the pull on the thread, and is therefore to be neglected. The component $M'b$ is that part of gravitation which shows itself as motion toward the vertical. As M' descends, the component $M'b$ decreases, and at M disappears entirely. Here the entire weight of the bob is exerted as a pull on the thread. But the required momentum carries the bob on to M'', and the component of motion, corresponding to $M'b$, reappears and increases until it overcomes the momentum and brings the bob to rest at M''. In passing from M'' back to M' the same course of events repeats itself in inverse order.

77. **Formula of the Pendulum.**—The displacement of the pendulum on either side of the vertical—that is, MM', or MM''—is called the *amplitude* of the vibration. The motion is periodic, and is found for small displacements to occupy practically the same time. We express this by saying that the vibrations are *isochronous.* It is upon this property that the value of the pendulum as a time-keeper depends.

The time of vibration of a pendulum commonly means the time that it takes the pendulum to pass from one extreme position (M') to the other extreme position (M''), and is represented by t. We find its value by developing the formula of the pendulum. This can only be rigidly carried out by means of higher mathematics, and so we must content ourselves here with a simple statement of the formula:

$$t = \pi\sqrt{\frac{l}{g}}.$$

78. **Discussion of Formula.**—This is a very simple formula, but one which involves large consequences. It shows that the time of vibration depends on two things—directly on the square root of length, and inversely on the square root of g. Consequently, to increase the time two, three, four or five fold, we should have to increase the length four, nine, sixteen, or twenty-five fold. This can readily be verified by experiment. Further, on account of the increase in

the value of g, a given pendulum vibrates more rapidly if taken from the equator to the poles.

79. **Time-keeping and the Seconds Pendulum.**—In the Cathedral of Pisa, and right next door to the celebrated Leaning Tower, there is still to be seen an antique lamp suspended from the roof by a long cord. It is said that away back in the year 1583 a boy by the name of Galileo noticed that the oscillations of this venerable lamp were extremely regular, and he was led to believe were isochronous. Experiment showed that he was right. By using a ball with strings of different length, he also discovered that the time varied as the square root of length. It was not, however, until 1656 that Huygens made use of the pendulum to mark time. Each swing of the pendulum is allowed to liberate a single tooth of an escapement wheel, and so regulates the rate at which the clock hand creeps around the dial.

To find the length of a pendulum which shall beat seconds at any given place, we have only to make $t = 1$, substitute the value of g for that place, and solve our time equation for l.

$$l = \frac{t^2 g}{\pi^2}. \quad (\pi = 3.14159.)$$

If $g = 980$, we have

$$l = \frac{980}{\pi^2} = 99 \text{ cm. (appr.).}$$

The length of the seconds pendulum is least at the equator and greatest at the poles, but even at the poles it is still a little less than a metre.

80. **Determination of g by the Pendulum.**—The pendulum gives us an indirect but at the same time very simple and accurate method for determining g. Knowing the length of the pendulum, and observing its time of oscillation, we have only to solve the time equation for g.

$$g = \frac{l\pi^2}{t^2}.$$

Nearly all determinations of g for practical purposes have been made in this way.

81. **The Compound Pendulum.**—We can not get a perfect bob and still less a rigid thread without weight or friction. But the simple pendulum is a capital example of the great usefulness of ideal machines in physical investigations. The law of the simple pendulum applies equally to the real or compound pendulum, if we calculate the length (l) of an equivalent simple pendulum. This equivalent length for the compound pendulum is the distance from the point of suspension to a point called the "centre of oscillation." We have seen that the time of oscillation depends on the square root of the length. Hence in a real pendulum all the particles in the upper part of the rod are retarded, and all the particles in the lower part of the bob are accelerated. But there must be one point on the axis which is neither retarded nor accelerated, and this is the centre of oscillation. Huygens found that the centre of suspension and the centre of oscillation are interchangeable—that is, the time of oscillation is not altered by using either centre for the point of suspension. This gives us a practical method for finding the centre of oscillation, and so calculating the length of the indwelling ideal pendulum.

PROBLEMS.—1. Will a change of temperature affect the time of oscillation of a compound pendulum, and why?

2. How could this variation be avoided?

REFERENCE.

For an approximate derivation of the formula of the pendulum, see Encyclopædia Britannica, article Mechanics, paragraphs 51 and 134: and for a rigid derivation see any standard work on higher mechanics or advanced physics.

CHAPTER XI

COMPOSITION AND RESOLUTION OF MOTIONS

82. **Composition of Motions.**—It is evident that a body can only move in one direction at one and the same moment; hence if two or more motions are impressed upon a body at the same time, these motions must be compounded into a single motion which represents the actual motion of the body. This process of substituting one motion for two or more separate motions we call the *Composition of Motions*, and the single motion thus substituted is known as the *Resultant*. It is convenient to represent these motions by straight lines which symbolize by their magnitude and direction the magnitude and direction of the motions themselves. In addition we must know where the motion starts, or its point of application.

When the motions are in the same direction and have the same point of application, the resultant is evidently equal to their sum.

When the motions are opposite in direction and have the same point of application, the resultant is their difference and is in the direction of the greater motion.

When, however, the motions are inclined to each other in direction and have the same point of application, the resultant will manifestly take a direction between the two motions and inclining to the greater motion. We can find its magnitude and direction by representing the two motions in magnitude and direction by straight lines drawn through a point and then constructing a parallelogram upon these lines as adjacent sides. The diagonal will represent the resultant. Thus, let the motions *A* and *B* have a common point of application, *O*, and construct the parallelogram *O A C B*. Then *O C* is the resultant.

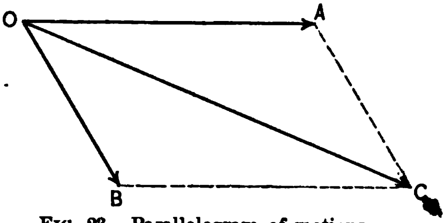


Fig. 23.—Parallelogram of motions.

The figure needs no demonstration. If we imagine the body to have a motion *A*, represented in magnitude and direction by *O A*, it is clear that under the action of that motion alone the body would move to *A*. Similarly, under the influence of the motion *B* alone, represented in magnitude and direction by *O B*, the body would move to *B*; but as these two motions take place at the same time, the body must respond to both impulses and move along a line *O C*, which will take it as far down as *B* and as far to the right as *A*. The point *C* fulfills both conditions.

83. **Parallelogram of Motions.**—This method of finding the resultant of two motions is of the utmost importance in mechanics. It is called the *parallelogram of motions* and is often stated as follows:

"If two motions impressed upon a body be represented in magnitude and direction by two straight lines drawn through the center of gravity of the body, and a parallelogram be constructed upon these straight lines as adjacent sides, then the resultant motion will be represented in magnitude and direction by that diagonal of the parallelogram passing through the center of gravity."

It is clear that the parallelogram of motions can be used to find the resultant of any number of motions by first finding the resultant of two of the motions, then compounding this resultant with the third motion, then this second resultant with the fourth motion, and so on until all are considered.

84. **Moments.**—If a pull or a push be exerted upon a body in a direction passing through the center of the body—that is, center of mass or center of gravity—the body if free will move along in the direction of the impulse. But suppose, now, that the direction of the pull or push does not pass through the center of the body or that one point in the body is fixed, what will happen?

In the first case the body will evidently turn until the direction of motion does pass through the center of gravity, and the body will then move in the given direction.

In the second case the body will turn about the fixed point as a center, and will only come to rest when the direction of motion, the center of gravity, and the fixed point are all in the same straight line.

This tendency to turn about a point has frequently to be considered in mechanics, and is measured in a special way by means of the *mechanical moment.* One can not speak of the moment of a motion, velocity, or force in the abstract, but must always speak of the moment with respect to some particular point. The moment is equal to the magnitude of the motion, velocity, or force multiplied by the perpendicular distance from the point to the line of motion, velocity, or force. This is illustrated in the following diagram:

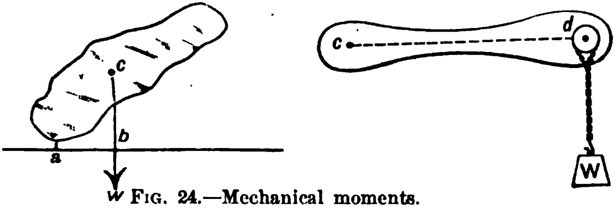


FIG. 24.—Mechanical moments.

In the first case an irregular stone, whose center of gravity is at *c*, rests upon the point *a*. The moment of the force of gravity upon it while in this position is $w \times ab$. In the second case a crank handle is fixed at *c*, and a weight, *w*, is hung from *d*. The moment of *w* with respect to c is $w \times cd$. This perpendicular distance $a\,b$ or $c\,d$ is known as the *arm* of the motion, velocity, or force.

The device of arms and moments, or, as we say of such formal agreements, the *convention*, is of great use in the analysis of machines.

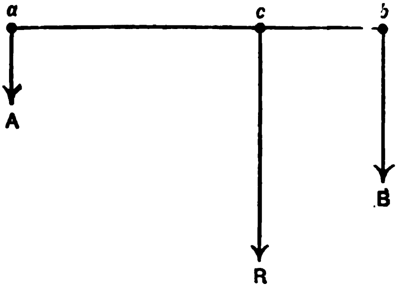


FIG. 25.—Parallel motions in the same direction.

85. Parallel Motions.—When two motions, not having the same point of application, are parallel in direction, they will fall into one of the three following classes:

1. *The motions are in the same direction, equal or unequal.*

The resultant is their sum, and the only question is as to its point of application. Let A and B be the two parallel motions. The resultant R is evidently equal to $A + B$. The point of application of R must be nearer to the larger motion B, and just in proportion to the relative magnitudes of A and B:

$$bc : ac = A : B,$$
$$\text{or, } A \times ac = B \times bc.$$

The moments of A and B with respect to c are equal and opposite, and hence both motions are duly represented in R. Had A and B been equal, $a\,c$ and $c\,b$ would have been equal also.

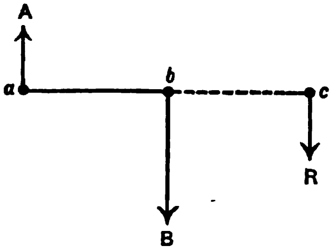


FIG. 26.—Parallel motions in opposite directions.

2. *The motions are opposite in direction and unequal.*

The resultant is their difference, and its point of application must be such that the motions A and B have equal and opposite moments with respect to the point; consequently it must be some point c in $a\,b$ produced, and such that

$$bc : ac = A : B,$$
$$\text{or, } A \times ac = B \times bc.$$

It will seem at first sight as if c should be between a and b, but that is impossible, for then the moments of A and B would re-enforce each other, instead of neutralizing each other.

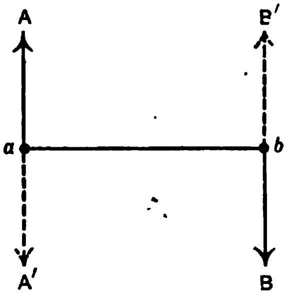


FIG. 27.—Mechanical couple.

3. *The motions are opposite and equal.*

This gives rise to a curious system in mechanics, known as a *couple*. In this case A and B, by statement, are equal, and if they had the same point of application their resultant would be zero. But separated as they are by the distance $a\,b$, their effect will be to turn $a\,b$ around until it, too, comes into the vertical and A and B are in the same straight line. Hence a couple has no resultant. Nor can this rotatory motion be neutralized by any single third motion. The body can only be kept at rest by opposing to $A\ B$ an equal and opposite couple, $A'\ B'$.

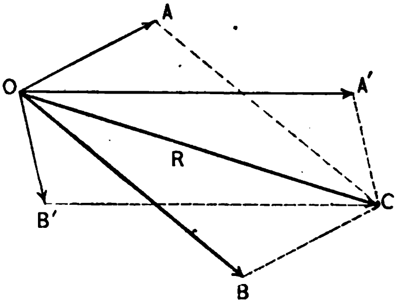


FIG. 28.—Resolution of motion.

86. **Resolution of Motions.**—In the *composition* of motions we substitute one motion for two. In the *resolution* of motion we do the reverse — we substitute two motions for one. Both processes are of immense importance in physics, and of frequent application. Any motion R may

be regarded as the diagonal of a parallelogram $OACB$, $OA'CB'$, etc., and may thus be resolved into two motions, A and B, A' and B', or into any other pair whatever, which may be represented as the adjacent sides of a parallelogram of which R is the diagonal.

This may seem like a very indefinite process, since the magnitudes and directions of the components may be almost anything we like. But in practice the direction of one or both components is generally given, and the resolution of R takes a more determinate form. We have examples of this in the pendulum, the inclined plane, and in many other machines and processes.

In the same way we may carry out the resolution of velocities and forces.

Problems.—1. Three equal motions imparted to a body leave it at rest. What angles do the motions make with one another ?

2. Four motions are given to a particle: E 24 centimetres, S 36 centimetres, W 18 centimetres, and N 30 centimetres. Find the magnitude and direction of the resultant.

Reference.

Elements of Mechanics : Oliver J. Lodge.
Matter and Motion : J. Clerk Maxwell.

CHAPTER XII

WORK, POWER, AND ENERGY

87. **Work** is the overcoming of resistance through space. Both elements are necessary to our conception of work. Motion through space against no resistance, or a force acting against a resistance but producing no motion, is doing no work. If we represent work by W, force by F, and space by s, our fundamental formula for work will be

$$W = Fs.$$

88. **Measure of Work.**—In the C.-G.-S. system the unit of work will be a unit of force acting through a unit of space—that is, one dyne (67) acting through one centimetre. Such a unit is called the *erg*. It is inconveniently small, however, and in practice we commonly use a multiple of this unit. The *joule* is 10,000,000 ergs—10^7 ergs—and for most purposes is a more convenient unit. Work is independent of time. An erg or a joule means a definite amount of resistance overcome through a definite space, but implies nothing with respect to the rate at which the work is done.

89. **Power.**—It is often important to express not only the amount of work done, but also the rate at which it is done. This is what we mean by *power*. It is the *rate* of doing work. The unit of power is unit work done in unit time—that is, one erg in one second. It is called the erg-second. This, like the erg, is inconveniently small, and is also commonly multiplied by 10^7. The unit so obtained is a joule-second, and is called a *watt*.

The Horse Power.—The usual units of work and power in the industrial world are the *foot pound* and the *horse power*. The *foot pound* is the overcoming of one pound resistance through one foot. As James Watt supposed that an average horse could lift 33,000 pounds through one foot every minute, he introduced the unit of power known as the *horse power*, H. P. It is 33,000 foot pounds per minute or 550 foot pounds per second. It is equivalent to 746 watts.

90. **Energy.**—It seems, then, that the work of the world is done by bodies in motion. Every moving body has in it the power of doing work, because by virtue of its own motion it can set other matter into motion. This power of doing work we call *Energy*. The whole drama of the world, physically speaking, consists in the transfer and transformation of energy. Remembering that energy is represented by matter in motion or matter capable of motion, we may say that the study of energy is the study of the universe. It is for this reason that we have put on the first page of this book,—Physics, the Science of Energy. Energy, like work, is measured in ergs and joules.

91. **Forms of Energy.**—The ability to do work and the effects produced in matter when work is done upon it show themselves in various ways and give rise to what are known as the forms of energy. These are all intimately related, and while it may be convenient at times to study the different forms under such separate headings as mechanical motion, sound, heat, light, magnetism, electric current, chemical affinity, and the like, we miss the main thought of modern physics as we do of modern philosophy if we allow these energy forms to take separate shape in our minds and get at all far apart. They are but qualities of the one essence —energy. We seldom have one of these qualities manifested alone. Any change in one quality, either in its intensity or in its continuance, involves similar and compensating changes in the other qualities. This is the deep

truth underlying the doctrine of the conservation of energy. You can not create energy or destroy it. Mechanical motion may stop, sound may cease, heat may disappear, light may be extinguished, magnetism may vanish, electric impulse may be lost, chemism may spend itself, but energy—the one eternal energy, of which these are the qualities or forms—energy goes on forever.

92. **Transfer and Transformation of Energy.**—We detect on all sides a tendency in energy to react with energy that is in a different state of excitement, and to stop reacting only when the two states are quite alike. This sums up the possibilities in the physical world. Bodies representing different degrees of energy meet and react. It is incorrect to say that one body acts on another, and to stop there. The truth is that both bodies are affected, one as much as the other. The reaction only ceases when the bodies possess the same degree of energy; but when this does occur they are quite indifferent to each other. Were all energy of the same intensity there would be perfect equilibrium.

93. **Newton's Laws.**—When the world of science was still very young—that is to say, about two centuries ago—Newton, with an insight that must always appear marvelous, expressed the main facts about motion and energy in three laws as following:

First Law: "Every body perseveres in its state of rest or of moving uniformly in a straight line except in so far as it is made to change that state by external forces" (Cause and Effect).

Second Law: "Change of motion is proportional to impressed force, and takes place in the direction in which the force acts."

Third Law: "Reaction is always equal and opposite to action—that is to say, the actions of two bodies upon each other are always equal and in opposite directions."

94. **Energy—Kinetic and Potential.**—Energy is not only represented by matter in actual motion and ready to do

work on the instant, as a hammer descending, but it is also represented by matter in such a position that it is capable of motion and ready to do work when the time comes, as a hammer poised. The energy represented by matter in actual motion is called *kinetic;* the energy represented by matter capable of motion is called *potential.*

Reciprocity.—When a moving body does work by giving up a part of its motion, it may be said to have *negative* work done on it. The body acted upon gains the motion lost by the body acting, and has *positive* work done on it. The algebraic sum of this negative and positive work is zero. In one sense, therefore, no work is ever done in the world. Energy is simply transferred.

CHAPTER XIII

MACHINES

95. **A machine** is a device for doing useful work. To do work is to overcome some sort of resistance through space. It is very obvious that a machine can not do this work of itself, but must be energized from without. The ability to do work depends upon the motion of the machine, and since this motion is so constantly spent in doing useful work, the supply must be constantly kept up. The motion is supplied by the expenditure of force—chemical, mechanical, or electrical; and since the rate of work is also important in all practical operations, the element of time comes in, and our force must be expressed in terms of power.

Hence we may say that a machine is a device for transforming power into useful work.

In our analysis of machines we shall speak of the work put into them as Power, p, and the useful work got out of them simply as Work, w. In this comparison no element of time comes in since they proceed simultaneously. If the machines were perfect and frictionless, the power put in and the work got out would be just equal in amount. But some of the power is always lost in doing internal work in the machine itself—that is, in overcoming the resistance or friction of the several parts. It is not lost in a mechanical sense; it reappears as heat and electricity, or is spent in wearing down the bearings. It is only lost in a utilitarian sense. The transformation of power into work is always effected, therefore, at the cost of some loss of power, and the best we can do is to reduce the loss to the smallest possible amount.

The *efficiency* of a machine is the ratio of work to power —that is, $\frac{w}{p}$—and expresses the exact percentage of power utilized as work.

96. **Axiom.**—*You can not get more work out of a machine than you put into it.*

Indeed, as we have just seen, you can not get as much, but the axiom is worth stating in this emphatic way, for it discredits at once all schemes for perpetual-motion machines. Perpetual motion itself is not only possible, but unavoidable, since motion can never be destroyed. But a "perpetual-motion machine" is a contradiction, for it implies the creation of energy on the part of a mechanism.

97. **The Principle of Virtual Velocities.**—But machines, though they create no energy, do possess advantages beyond their mere ability to transform power into work. While the amount of useful work is always less than the amount of power consumed, we can accomplish tasks greater in magnitude by the use of machines than we could possibly accomplish without them. If we are willing to spend power over a long period of time and accomplish work at a very slow rate, we can move mountains, and justify the boast of the old philosopher who said that he could move the world *if* you would only give him a place to stand on. Let us see how this is.

$$\text{Work} = \text{Force} \times \text{Space, or } W = Fs.$$

Since work is made up of two factors, force and space, we may vary these to suit ourselves, making either one large and the other one correspondingly small. Thus, if we make s large, F will be small, and our machine will overcome only a small resistance, but will do it through a large space. On the other hand, if we make s small, F may be very large, and our machine will be a veritable Hercules, overcoming tremendous resistance, but doing it through a very small space—that is, very slowly.

Meanwhile the power put into the machine has been a constant quantity. This is also represented by force acting through space. Machines are said to have a *mechanical advantage* when the force-element in the work is greater than the force-element in the power. The difference in the spaces passed over preserves the equality between the two amounts of energy. We sum this all up in the *principle of virtual velocities:*

"The force put into a machine, multiplied by the space through which it acts, is always equal to the force got out of a machine multiplied by the space through which *it* acts."

98. **Simple Machines.**—The five simple machines, known as the *lever*, the *wheel and axle*, the *inclined plane*, the *pulley*, and the *screw*, occur in all sorts of mechanisms, and have many important applications in daily life. They may be analyzed by means of the principle of virtual velocities, or by applying the principle of moments. We shall use either method and sometimes both. We shall always represent the force put into the machine by p, and the space through which it acts by d, and its arm by a. In the same way we shall represent the force got out by w, the space passed over by s, and the arm by b. (See Fig. 32.)

The process of mechanical analysis is very simple. It consists in finding the relation between p and w, and proceeds by applying one or both of the fundamental formulæ of machines:

1. (Virtual Velocities), $pd = ws$.
2. (Moments), $pa = wb$.

99. **The Lever** consists of a rigid bar supported at one point, called the fulcrum, f, and capable of turning freely about this point. There are three possible arrangements in the disposition of fulcrum, pressure, and weight, and this gives rise to the three classes of levers:

1. *The lever of the first class* has f in the midway, and consequently p and w at the ends.

2. *The lever of the second class* has w in the midway, and consequently f and p at the ends.

3. *The lever of the third class* has p in the midway, and consequently f and w at the ends.

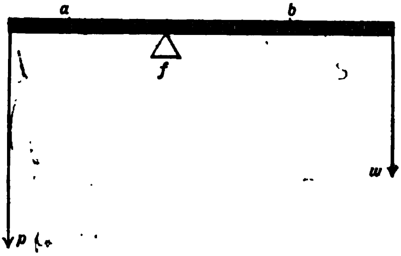


FIG. 29.—Lever of the first class.

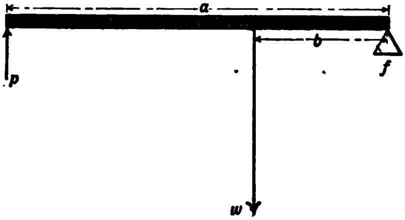


FIG. 30.—Lever of the second class.

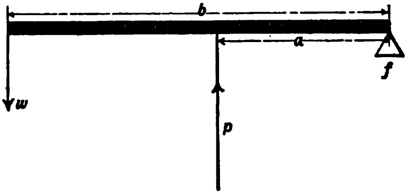


FIG. 31.—Lever of the third class.

Analyzing 1 by virtual velocities, we have (Figs. 29, 32):

$$ws = pd, \text{ or } w = \frac{d}{s}p.$$

If d is greater than s, there is mechanical advantage; if less than s, mechanical disadvantage. In the first case the fulcrum will be nearer w; in the last case, nearer p. In the figure, d is two thirds of s, since a is two thirds of b; hence $\frac{d}{s} = \frac{2}{3}$, and there is mechanical disadvantage.

Analyzing 2 by moments, we have (Figs. 30, 33):

$$wb = pa, \text{ or } w = \frac{a}{b}p.$$

The arm a is the distance of p from the fulcrum, and the arm b is the distance of w from the fulcrum. It is evident that the moments must be taken with respect to f, since that is the only fixed point, and consequently any motion must be about f as a center.

In levers of the second class it is evident that there must always be mechanical advantage, since *w*, having the shorter arm, must always be greater than *p*.

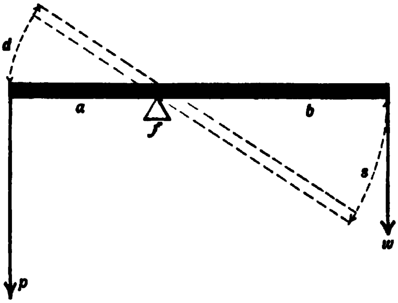


Fig. 32.—Analysis of the lever of the first class.

Analyzing 3 by both virtual velocities and moments, we have (Figs. 31, 34):

$$ws = pd,$$

$$\text{or} \qquad w = \frac{d}{s} p. \qquad (1)$$

$$wb = pa,$$

$$\text{or} \qquad w = \frac{a}{b} p. \qquad (2)$$

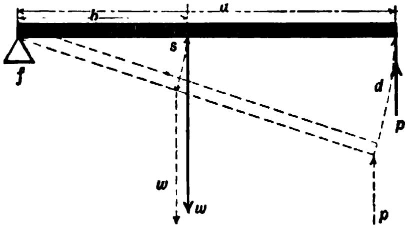


Fig. 33.—Analysis of the lever of the second class.

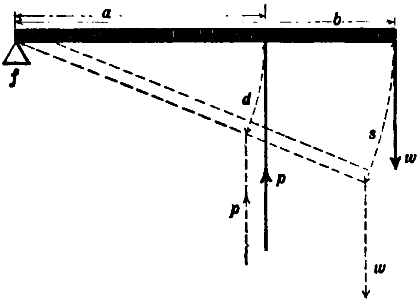


Fig. 34.—Analysis of the lever of the third class.

In levers of the third class there can never be mechanical advantage, since *p* is always nearer to *f*, and must therefore be greater than *w*. The arms *a* and *b* are the radii of the circles over which *p* and *w* move when displaced, and of which *d* and *s* are the actual arcs passed over. Since circumferences of circles are to each other as their radii ($c = 2\,\pi r$, and $c' = 2\,\pi r'$), the corresponding arcs *d* and *s* must be as the radii of their respective circles—that is, $\frac{d}{s} = \frac{a}{b}$, a relation which would have to be true if 1 and 2 are both true. The principle of moments is indeed but a special statement of the principle of virtual velocities.

Applications.—These are almost too numerous to mention.

First class: Crowbar, balances, walking beam, steelyard, seesaw, scissors (double).

Second class: Crowbar (when resting against the ground), nut crackers (double), wheelbarrow, oars, canoe paddle, bicycle pedal.

Third class: Spring shears, pincers, fire tongs, foot treadle.

Note.—The analysis of the lever is, after all, but a special application of the study of parallel forces. Should the forces of either pressure or weight be applied obliquely, it would be necessary to resolve them into two components, one at right angles to the lever and the other in the direction of the lever. We should only consider the component at right angles to the lever, since this would be the only one capable of producing motion about the fulcrum. It should also be added that we have throughout neglected the weight of the lever itself. In practice this must be taken into consideration, but the correction may easily be made.

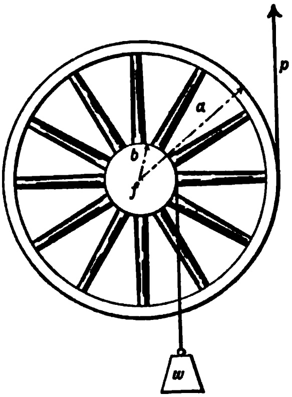


FIG. 35.—Wheel and axle.

100. The Wheel and Axle.—This is practically an application of the lever, the fulcrum being the common axis of the wheel and the axle. Our analysis can best be made by help of moments. The arm of the weight is the radius of the axle, b; the arm of the pressure is the radius of the wheel, a. As before,

$$wb = pa, \text{ or } w = \frac{a}{b}p.$$

The wheel and axle, arranged as shown, will always give a mechanical advantage expressed by $\frac{a}{b}$.

The wheel and axle find application in such special machines as the windlass and in many complex mechanisms.

101. **The Pulley.**—In its simplest form the pulley is a fixed wheel, which serves to change the direction of motion, but offers no mechanical advantage. As P and W (Fig. 36) move through the same distance, they must be equal.

$$W = P.$$

In this form it is simply a lever of the first class (Fig. 32), in which a and b are equal.

Where the pulley is movable (Fig. 37), and one end of the rope is fixed at C, the force P moves through twice the distance that the weight, W, is raised, and consequently

$$W = 2P.$$

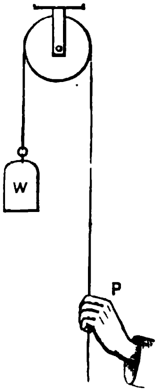


FIG. 36.—Simple pulley.

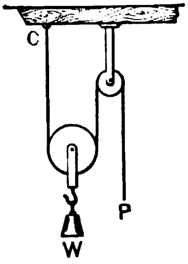


FIG. 37.—Movable pulley.

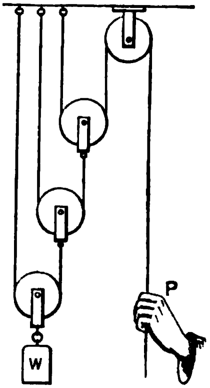


FIG. 38.—Series of movable pulleys.

In this form it is simply a lever of the second class (Fig. 33), in which $a = 2b$.

By arranging a suitable system of movable pulleys, almost any mechanical advantage can be secured. It is, of course, at the expense of speed. Each movable pulley diminishes the speed one half, and increases the weight that any given force can raise twofold. Such an arrangement is shown in Fig. 38. In this case we have the force P multiplied by two for every movable pulley employed. Hence if n be the number of movable pulleys employed, we shall have

$$W = 2^n P.$$

In the figure $n = 3$, and so $W = 2^3 P = 8 P$.

It is more convenient in practice to arrange one fixed block containing several pulleys on the same axle, and one movable block also containing several pulleys on a common axle. This is shown in Fig. 39. Here there is only one rope, whose fixed end is attached to the fixed block. The rope then passes alternately over the pulleys of the two blocks, and finally emerges from the upper block, passing downward for the application of the force P. In this case the fixed pulleys in the upper block contribute nothing to the mechanical advantage. The pulleys in the movable block add each a twofold advantage; hence, if n be the number of pulleys, the relation will be

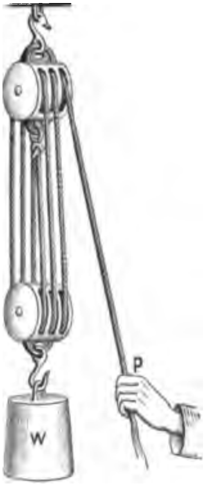


FIG. 39.—Compound block pulley.

$$W = 2\,n.P.$$

102. **The Inclined Plane** in its simplest form is a device for lifting weights which would otherwise be inconveniently or impossibly great. It may be analyzed in two ways, either by virtual velocities or by resolving the weight into two components, one acting along the inclined plane and one at right angles to it. In Fig. 40 w is to be lifted through the height s, but p may move through d. Hence

the advantage is greater the longer *d* is, with respect to *s*—that is, the smaller the angle of the plane — *a*.

$$ws = pd, \text{ or } w = \frac{d}{s}\ p.$$

As *a* increases from 0° to 90°, we can easily see that the pressure, *p*, must be increased, as the plane gets steeper, and will finally equal the weight, *w*, when the plane is vertical. Then $w = p$.

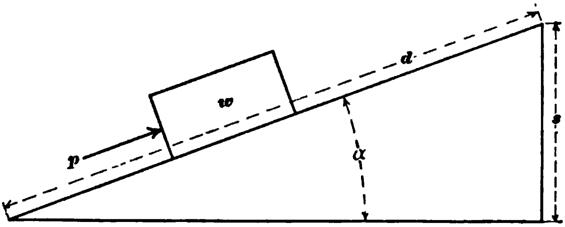


FIG. 40.—Inclined plane.

In Fig. 41 the weight is represented by a straight line, *c g* (which, as we have seen, must always be vertical and must start from the center of gravity, *c*). This is the only force acting on the body. But the body can not move in the direction of *c g*. It can only move down the inclined plane, and this it will soon proceed to do unless we stop it.

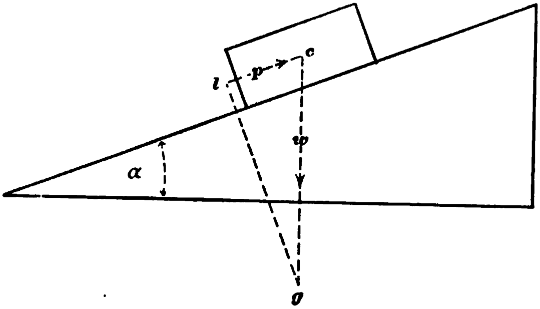


FIG. 41.—Analysis of inclined plane.

Hence the weight cg must be resolved into a component, cl, parallel to the plane, and a component, lg, at right angles to the plane. This last component shows itself as pressure against the plane and does not concern us here. The component, cl, represents the motion down the plane, and must be met by a force, lc, equal and opposite to cl, if the body is to be supported on the plane. lc represents the pressure, or p. Hence,

$$w : p :: cg : lc$$
$$w \times lc = p \times cg$$

Whichever method of analysis we use, we get the same result.

The *Wedge* is simply a double inclined plane, in which the pressure is exerted at right angles to the common back —that is, in the line of the common base. It has application in all our cutting tools, such as the knife, chisel, and axe. It has also direct use in splitting timber and in separating layers of rock.

103. **The Screw.**—The usual form of the screw, such as is seen in a copying press, may be regarded as a combination of an inclined plane and the wheel and axle. The screw thread is simply an inclined plane wrapped around a cylindrical support. The pitch of the screw—that is, the vertical distance between two neighboring threads—is the height of the plane. The thread corresponding to one complete turn is the slant length of the plane, and the circumference of the screw corresponds to the base of the plane. The force is generally applied to the circumference of a wheel mounted on one end of the screw. We can best analyze the

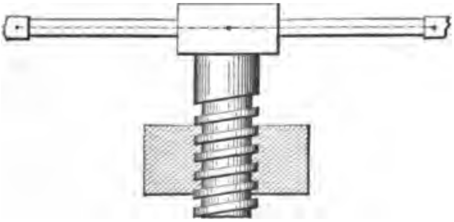


FIG. 42.—Screw.

screw by means of the principle of virtual velocities. Thus the force, p, moves through the circumference of a circle, whose radius, r, is the radius of the wheel, while the weight, w, advances a distance equal to the pitch of the screw.

$$ws = pd.$$

$$w \times \text{pitch} = p \times 2\pi r.$$

$$w = \frac{2\pi r}{\text{pitch}} \cdot p.$$

By making the wheel large and the pitch small, we can get a tremendous mechanical advantage. The screw has many applications besides the copying press. By means of powerful jack screws, a whole building can be lifted from its foundations. The screw is used in the lathe and other mechanisms, and in many physical instruments, as the micrometer screw, to say nothing of its manifold use as clamp, fastener, and leveler.

Experiments.—1. Take a straight bar of strong, sound wood, about 1 metre long and 2.5 centimetres square, and find its weight by weighing a simple bar, 5 to 10 centimetres long, and of the same cross-section. By this method one can get an accurate result, and use a delicate balance. Let this weight be x.

2. Balance the lever thus obtained on the sharp edge of a triangular piece of wood, used as a fulcrum, mark the fulcrum f, and see if it is in the center of the lever.

3. Put unequal weights on the ends of the lever; balance it afresh; measure the two arms, and calculate the moments of the two weights. Allowing for the unequal weights of the two arms, are the moments equal?

4. To weigh the lever by moments. Take the same lever, add a suitable weight, w, to one extreme end, and balance, marking this fulcrum f'. Designate the distance from w to f' as the arm b. The moment is then wb. The force on the other side of f' is the weight of the lever, p, and its arm, a, is the distance $f'f$, since the weight of the lever will act as if concentrated at its center of gravity f. The moment is pa. $wb = pa$, or $p = \frac{b}{a} \cdot w$. Is this equal to x as obtained in Ex. 1?

5. Mark one end of the lever *c*, and the other end *d*. Support *d* on the triangular fulcrum, and *c* by means of a spring balance. Take the reading *r*. Add a known weight, *y*, to any point of the lever, *g*, and take a second reading, *r′*.

Does $(r' - r) \times cd = y \times gd$?

6. Repeat the experiment, placing the spring balance at *g* and the weight *y* at *c*. What now is the result?

7. In the same way, take two boards of equal length, *l*, and support as above, with a narrow crack between. Support *w* by a strong, light thread, passed through the crack, and fastened to the spring balance. Keeping balance and thread horizontal, determine the relation between *w* and *p*.

Problem.—1. Can the wheel and axle be so arranged that it will give a mechanical disadvantage? If not, or if so, explain the reason.

2. Determine the mechanical advantage in the case of the inclined plane, when the force *p* is applied parallel to the base, giving your result in terms of the base and height of the plane.

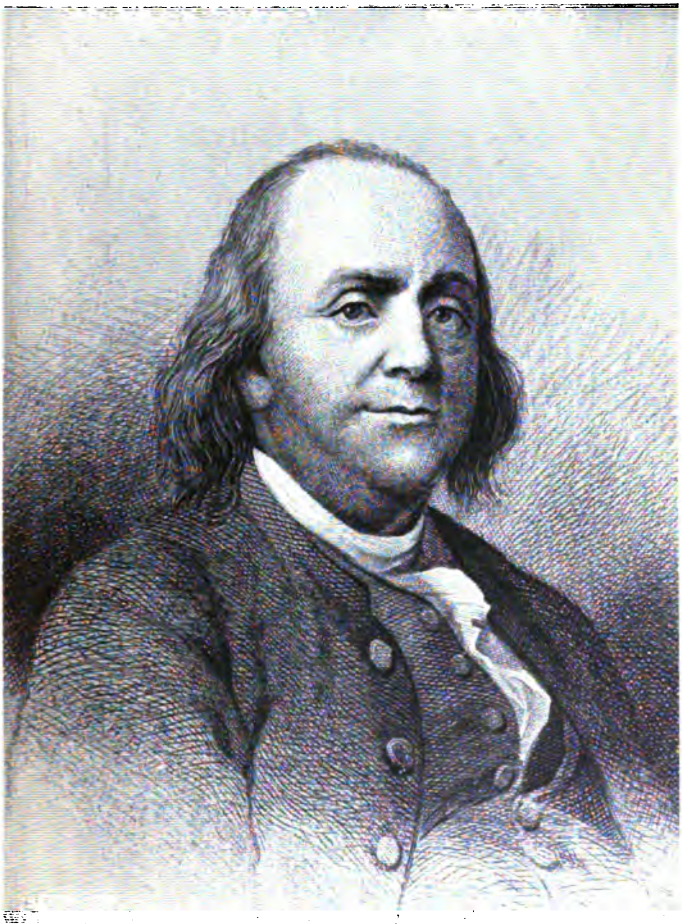
BENJAMIN FRANKLIN (1706–1790)

Franklin was born in Boston, January 17, 1706. At seventeen years of age he hired out as a printer in Philadelphia. He became the leading journalist of America. For twenty-five years he published Poor Richard's Almanac, which attained a marvelous popularity.

He acquired familiarity with French, Spanish, Italian, and Latin. He became America's leading diplomatist and statesman. He was one of the committee of five which wrote the Declaration of Independence; a member of the commission appointed to negotiate peace with England at the close of the Revolutionary War; a leading member of the first National Convention elected to frame the Constitution; and American minister to France for nine years.

His principal scientific researches were upon balloons and atmospheric electricity. He was a member and one of the managers of the Royal Society, London, and a member of the Royal Academy of Sciences, Paris. Together with a committee of the French Academy, he investigated mesmerism at the request of the King of France, which resulted in the disgrace and flight of Mesmer.

McMaster, in the History of the People of the United States, vol. i, pp. 233 and 422, says: "He was renowned throughout Europe as a philosopher; nor has his just fame been cast in the shade by any investigator our country has since produced." "Franklin was in truth the greatest American then living; nor would it be safe to say that our country has since his day seen his like."



BENJAMIN FRANKLIN.

MECHANICS OF FLUIDS

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CHAPTER XIV

PRESSURE IN LIQUIDS

104. **General Definition of Fluids.**—We designate both liquids and gases as *fluids*, because both are characterized by the great mobility of their molecules. But there is a great difference between the two in the matter of compressibility. Liquids are so little compressible that we are almost justified in speaking of them as Incompressible Fluids. Gases, on the other hand, respond so perfectly to every change of pressure that we may properly speak of them as Compressible Fluids. This distinction will need to be kept in mind in our study of pressure in liquids and in gases.

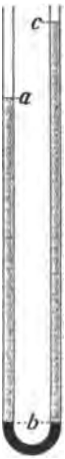

Fig. 43.

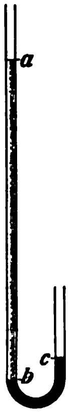

Fig. 44.

105. **The Mercury Pressure Gauge.**—A very convenient instrument for the study of pressure in fluids is the mercury pressure gauge shown in Figs. 43 and 44. In Fig. 43 a column of water, *a b*, is represented as being balanced by a column of alcohol, *b c*, both columns resting upon mercury in the part of the tube below *b*. In Fig. 44 the column of water, *a b*, is balanced by a column of mercury, *b c*. In both cases it is obvious that the mercury acts as a sort of scales for weighing. In Fig. 44 the column of water, *a b*, has forced the mercury down to *b* in the

left arm of the pressure gauge and up in the right arm until it supports a column of mercury, *b c*, equal in weight to itself. In Fig. 43 the column of water *a b* is equal in weight to the column of alcohol *b c*.

106. **Pressure in Terms of Inches of Mercury.**—We may speak of the pressure in terms of inches of mercury. Thus the pressure of a column of water 13.6 inches long is about equal to a column of mercury one inch long; half an inch of mercury would represent the pressure of a column of alcohol about eight and a half inches long. In inflating a football one is likely to exert a pressure of about three inches of mercury. The ordinary pressure upon a steam radiator is likely to be about ten inches of mercury. That is, if we connect one arm of a mercury pressure gauge with the inflated football or the steam radiator these pressures would force the mercury up in the other arm of the pressure gauge three inches in the first case and ten inches in the second case.

107. **Pressure in Terms of Pounds per Square Inch.**—We usually speak of pressure in terms of pounds per square inch. In Fig. 45 the column of water *a b* is represented as having a cross-section of one square inch and a height of 13.6 inches. It is balanced by a column of mercury *b c*, which is a cubic inch in volume. Now, a cubic inch of mercury weighs about half a pound; the weight of the column of water is, therefore, about half a pound; the pressure upon the square inch of surface of mercury where the water rests upon it is half a pound. It is manifest that if the cross-section of the tube were half as large there would be half the quantity of water, and half the weight—i. e., one quarter of a pound upon half a square inch; or if the tube were one quarter or one tenth as large in cross-section the weight of water would be one quarter or one tenth as

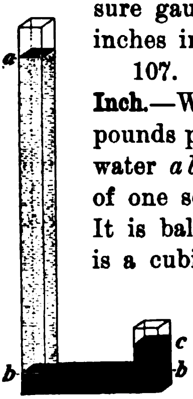

FIG. 45.

much. The pressure would, however, in all cases be *at the rate of* one half pound to the square inch, so long as the height of the column remained 13.6 inches. And let the diameter of the column *a b* be never so small or great it will in every case balance the cubic inch of mercury *b c*, provided its height remains 13.6 inches.

108. **First Principle.**—(a) *Pressure in liquids is proportional to the depth alone, and is not influenced by the size or shape of the vessels which contain them.* (b) *At any given depth the pressure is equal in all directions.*

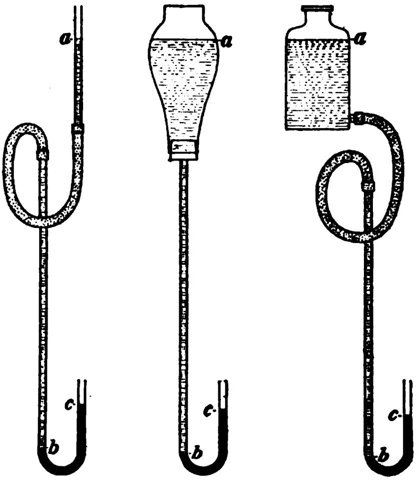

FIG. 46.

The first part of this principle may be illustrated by such apparatus as is represented in Fig. 46, and the second part is shown by such apparatus as is represented in Fig. 47; *a b* is in each case the depth of the water measured *vertically*, and *b c* is in each case the mercury column sustained by the pressure of the liquid. In all cases *a b* is found to be 13.6 as long as *b c.*

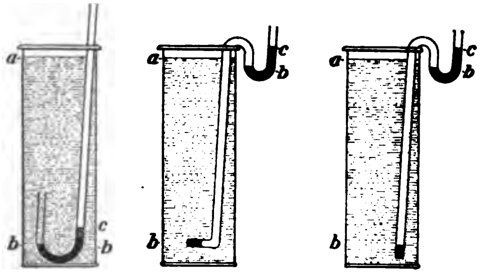

FIG. 47.

109. **Pressure is due wholly to Gravity.**—A few diagrams, such as those represented in Fig. 48, may help one to feel that it is not unnatural that the pressure of gravity upon particles of matter free to move among themselves will result in pressure sidewise or even upward. Having no single point or even surface of support, liquids do not, like solids, exert a downward force of mg (mass multiplied by the acceleration of gravity; sections 65 and 69) on the bottom of the containing vessel. The pressure upon any point of surface depends not on the amount of liquid, but entirely upon the height of the liquid above the center of the unit surface.

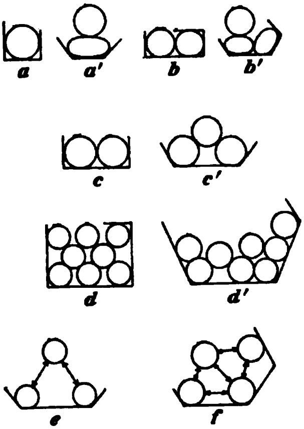

Fig. 48.

In Fig. 49 the vessels have all the same-sized bases, and the water stands at the same height in all. The amount of water in the several vessels is manifestly very different, but the pressure upon the base of each vessel is the same. This seems at first sight an evident paradox. The weight of water on the base *A* is manifestly the whole weight. But this is equal to the volume of the cylinder in cubic centimetres (since one cubic centimetre weighs one gram), and the volume is equal to the height multiplied by the area of the base. By contracting the sides, as in *B*, the amount of water is greatly reduced, but the

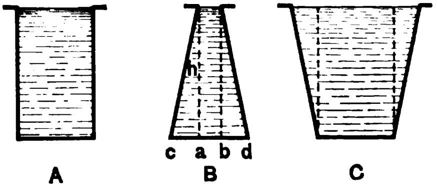

Fig. 49.

pressure on the base remains the same. The pressure on the portion of the base *a b* is equal to a volume of water, *h* × *a b*. This has the same intensity per unit surface as in *A*, since the height, *h*, is the same. But we could not have a greater pressure on *a b* than at *c* and *d*, for in that case there would be a flow of water toward *c* and *d* accompanied by depression of the column which stands over *a b* and a reduced pressure on *a b*; but we know from our experience that no such flow does take place. The pressure on the base *a b* is transmitted equally in all directions, and acts downward at *c* and *d* with precisely the same force as it does on *a b*. In the vessel *C* there is more water than there is in *A*, but there is no increase of pressure on the base.

110. **Upward Pressure in Liquids.**—Because liquids transmit pressure equally in all directions, it follows that at any depth the upward pressure due to the weight of the liquid must be exactly the same as the downward pressure. Consider the level *a a* in the tank of water shown in Fig. 50. The downward pressure on a square centimetre, *b c*, is the height of a column of water *b c* × *h*. If this pressure were not counterbalanced there would be a downward movement of the liquid. But no such movement takes place. Every square centimetre on the level *a a* has the same downward pressure of *h* grams, and that pressure, being transmitted equally in all directions, acts upward on *b c* and just counterbalances the downward pressure.

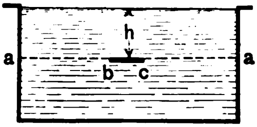

FIG. 50.

The upward pressure of liquids is illustrated by a simple experiment. An open glass cylinder (Fig. 51) with ground edges has one end closed by means of a thin ground-glass cover plate. In the air the plate has to be held up against the cylinder, but as soon as cylinder and plate are immersed to a depth of about one centimetre in water, the upward pressure of the water holds the plate against the cylinder. The deeper the cylinder is pushed the greater the upward pressure, and the more securely is the plate held against the cylinder. If now water be poured into the cylinder, the cover plate will fall when the water in the cylinder is *nearly* at the same level as the water outside in the tank. The difference in level represents the volume of water whose weight just equals that of the cover plate. Had the cylinder been filled with alcohol, or some liquid lighter than water, the level inside the cylinder would have to be considerably higher than the level outside to make the cover plate fall off.

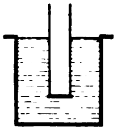

FIG. 51.

The *upward* pressure on the plate is equal to the weight of a column of water having the plate for its base, and a height equal to the distance from the surface to the lower face of the plate. The *downward* pressure is equal to the weight of the liquid inside the cylinder, plus the weight of the plate itself.

This upward pressure of liquids is manifested when you raise the tubular stopper in a bath tub full of water. The water rushes up the tube by reason of the pressure of the surrounding water.

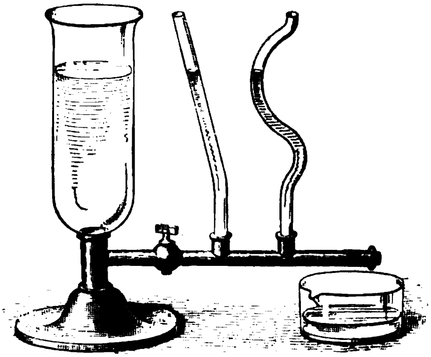

FIG. 52.

111. Liquids seek their own Level.—If we have several communicating vessels, as shown in Fig. 52, and pour water into one of them, we notice immediately that the water rises in all of them to the same level. We can not fill one vessel without filling all. On the whole, we should expect this, for if we imagine for a moment that we have succeeded in filling one vessel without filling the others, and look at the pressures, we shall find an impossible state of affairs. The liquid in the first vessel will be unsupported at the outlet into the second vessel. With the second vessel empty, there will be nothing to balance that pressure and nothing to prevent the liquid from flowing out, which it accordingly does. The pressure is only balanced at each outlet when the liquid stands at the same height in each vessel. This is popularly expressed by saying that liquids seek their own level. Every free surface of water, unacted upon by wind or current, is perfectly level, and is perpendicular to the direction of gravity. Consider for a moment the force at work. The only force is gravity, and this always acts vertically downward. If the surface were not level, but were inclined, as indicated in Fig. 53, we should have at *a* a downward pressure, represented by the arrow. This pressure is transmitted equally in all directions, and consequently acts upward at *b*. In the absence of any corresponding downward pressure at *b* the water rises at *b*, and must sink at *a*, only coming to rest when in all parts of the liquid, the downward pressure and the upward pressure, are the same. We can sum this up by saying that the surface of liquids is always perpendicular to the direction of force acting upon them. Consequently the surface of a still pond or lake is always level, since it is everywhere perpendicular to gravity. In the case of the ocean or of large bodies of water generally, the direction of gravity changes about 1° every 69 miles, and consequently the surface, being perpendicular to gravity, is always changing, and is in reality spherical. Of course, the surface of small ponds and lakes

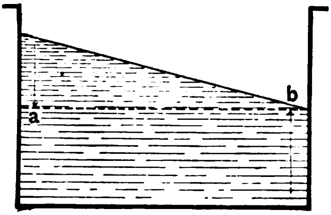

FIG. 53.

is also strictly spherical, but in such small distances the departure from a strict plane is not noticeable.

112. **Buoyancy.**—From what we have learned thus far we know that any object which sinks beneath the surface of a liquid will have pressure exerted upon it proportional to the depth which it sinks into the liquid, and due wholly to the weight of the liquid. Let us consider the forces acting upon a cubic centimetre of water, *a*, Fig. 54, in a tank of water. Let us suppose the upper surface of the cube *a* to be 1 centimetre below the surface of the water in the vessel. On the upper face of the cube there will be a downward pressure equal to 1 gram, the weight of the column of water above it. The horizontal pressure upon the four faces may be neglected, since they come from four directions at right angles and just balance one another. On the lower face of the cube there will be an upward pressure of 2 grams, equal to the weight of a column of water, whose height is 2 centimetres and whose cross-section is 1 square centimetre. The downward pressure of water upon the upper face of the cube is 1 gram, and the upward pressure of water upon its lower face is 2 grams. But the cube does not move upward, because its own weight is 1 gram. All the forces are balanced, and the cube of water stands still. This would of course be true also of a cubic centimetre of any other substance which weighed exactly 1 gram. Let us substitute for the cube of water a cube of wood about half as heavy as water. The downward forces will be the weight of the wood and the weight of the column of water above it, equal to 1½ grams. The upward force will be equal to 2 grams, as before. Hence there will be an unbalanced buoyant force of half a gram, and the wood will move upward until it reaches a place where the opposing forces are equal. Pursue this method of reasoning, and find out that it must rise until it displaces

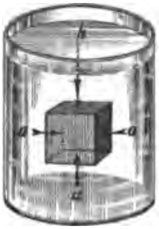

FIG. 54.

just its own weight of water—i. e., until only half of the cube is submerged. Had the cube been of cast iron, density 7.2, supposing it to be in its original position, the upward pressure upon its lower face would be 2 grams, as before, and the downward pressure would be its own weight—7.2 grams plus the weight of the 1 centimetre of water above it, 1 gram, making a total downward force of 8.2 grams. Hence the cube would sink with a force of $8.2 - 2 = 6.2$ grams. Suppose the bottom of the vessel is 5 centimetres below the surface of the water and the iron cube to be resting upon it. What would be the buoyant force upon it, and with how much force would it press upon the bottom of the vessel? If this cube of iron were suspended upon a string at various depths within the liquid, but always wholly submerged, would it in every case pull with the same force upon the string? Would your answer be the same if liquids were compressible? Balloons may be made to float higher or lower in the air by increasing or decreasing their weight. This is not possible with objects wholly submerged in liquids. It is a matter of daily experience that as soon as a floating object becomes heavy enough to sink beneath the surface of the water it goes straight to the bottom. The only way to prevent this would be to have liquids of different densities, and which do not readily mix, arranged in layers one above the other. If a vessel is half full of water, density 1.00, and half full of ether, density .71, a block of oak, density .85, dropped into the vessel will sink to the bottom of the ether layer and float on the water underneath. An egg will sink in fresh water and float in salt water. Consequently if a jar be half filled with salt water and then fresh water be carefully added, an egg dropped into the jar will sink halfway, and remain suspended at the meeting plane of the two liquids. From such investigations we may deduce the principle that a body wholly submerged in a liquid is buoyed up by a force exactly equal to the weight of its own volume of the liquid.

This is prettily illustrated by the apparatus represented in Fig. 55. The upper cylinder is hollow, the lower cylinder solid, and has such a volume as to exactly fit inside of the upper cylinder. They are suspended as shown in the figure, and carefully balanced. Then water is poured into a vessel so as to submerge the lower cylinder. Its buoyant force lifts the left arm of the balance. The upper cylinder is then filled with water, and this is found to restore the balance, showing that the buoyant force upon the submerged cylinder is exactly equal to the weight of its own volume of water. The same experiment may be performed less elaborately by weighing any solid of known volume, say *n* cubic centimetres, first in air and then in water. The loss of weight will be just *n* grams.

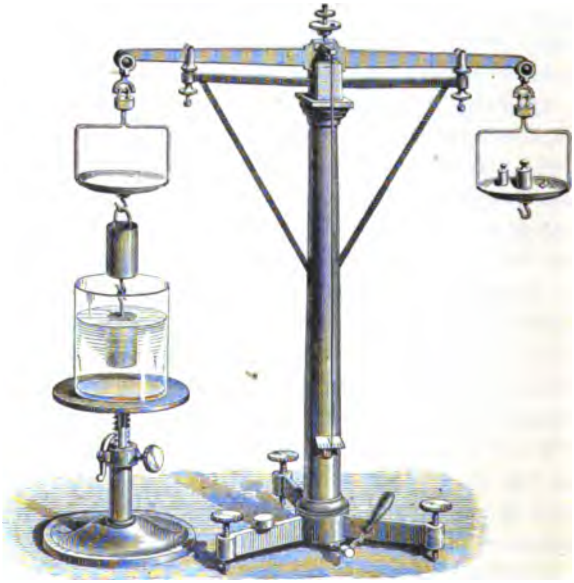

Fig. 55.—Principle of Archimedes.

Every boy who has lifted a stone under water knows how heavy it suddenly becomes when he tries to bring it above the surface. The transporting power of running water is greatly increased by the buoyancy of the water and the consequent loss of weight on the part of the material carried.

We may make use of this principle to find the volume of an object. For example, if an object weighs 3 grams in air and 2 grams when wholly submerged in water, the buoyant force of the water is 1 gram—i. e., its volume is 1 cubic centimetre.

113. Specific Gravity.—It is obvious that the object mentioned in the last paragraph was three times as heavy as water. We express this by saying that its specific gravity is 3.

The balance may be used to determine the specific gravity of both solids and liquids.

a. Solids.—A fine silk thread or wire is tied around the solid and a loop made of the end several inches away from the solid, so that the whole may be freely suspended from the arm of the balance (Fig. 56). The weight is then taken in air. Let this be represented by x. A glass of water is now brought under the solid and raised until the entire solid is covered by the water. The solid must, of course, swing freely in the water, and not touch the sides of the beaker. The weight is taken in water. Let it be represented by y.

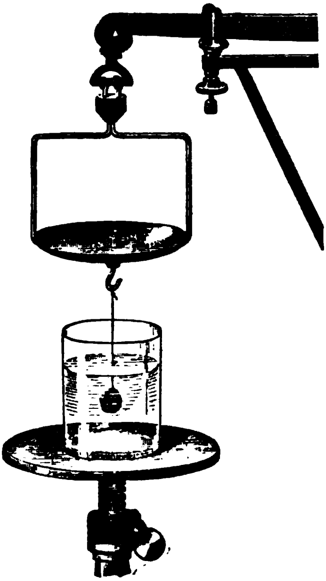

FIG. 56.—Specific-gravity balance.

Then $x - y$ will represent the *loss* of weight in water, and we will have

$$\text{specific gravity} = \frac{x}{x - y}.$$

Example.—A piece of limestone rock.

Weight in air $= 17.65$
Weight in water $= 10.99$
Loss of weight in water $= 6.66$

$$\text{Specific gravity} = \frac{17.65}{6.66} = 2.65.$$

That is to say, limestone is nearly two and two thirds times as heavy as an equal volume of water.

b. Liquids.—To determine the specific gravity of a liquid we must know the weight of a given volume of it, and also the weight of the same volume of water. The ratio of one to the other is the specific gravity. We can easily find these two quantities by taking a suitable glass plunger of known weight (x) and weighing it first in the liquid whose specific gravity is to be tested (y) and then in water (z). The loss of weight in each case will evidently be the weight of a volume of liquid equal to the volume of the plunger, and we shall have specific gravity $= \frac{x - y}{x - z}$.

Example.—Alcohol.

Weight of plunger in air $= 10.21$ grams (x)
" " " alcohol $= 8.45$ " (y)
" " " water $= 8.02$ " (z)

$$\text{Specific gravity} = \frac{10.21 - 8.45}{10.21 - 8.02} = \frac{1.76}{2.19} = .8$$

We have two kinds of hydrometers for determining specific gravity, the hydrometer of *constant volume* and the hydrometer of *constant weight.*

By the first we can determine the specific gravity of both solids and liquids. A form of the instrument, known as Nicholson's hydrometer, is shown in Fig. 57.

The solid whose specific gravity is to be determined is placed on the upper scale pan and weights added until the hydrometer sinks to the index point. The solid is then placed in the lower pan under water and weights added to the upper scale until the buoyancy of the now submerged solid is compensated. The added weights represent the weight of the water displaced by the solid. This divided into the weight of the solid gives its specific gravity. In using the hydrometer for liquids it is simply floated in the liquid and then in pure water, and the weight of the hydrometer itself, plus the added weights, will give the weights of the liquid and of the water displaced. One divided by the other is the specific gravity.

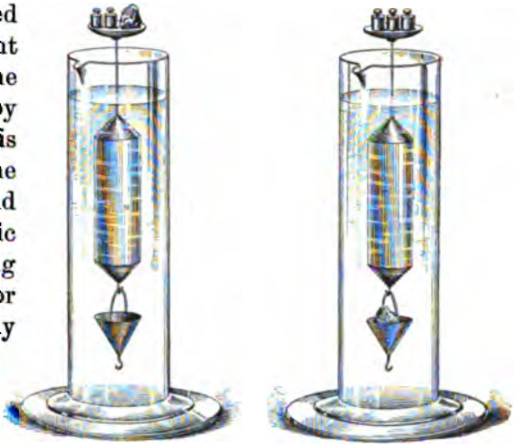
FIG. 57.—Hydrometer of constant volume. (Nicholson's.)

The *hydrometer of constant weight* may be used only for liquids. It is made of glass, and consists of a cylinder or tube, terminating below in a bulb loaded with mercury or shot, and above in a long slender tube which carries a scale and projects above the surface when the hydrometer is floated in water (Fig. 58).

Now, in order that any solid may float, it must displace an amount of liquid whose weight is just equal to its own weight. Hence when the hydrometer is put into liquids lighter than water it sinks deeper, and when into liquids heavier than water it rises higher above the surface. If the point on the scale to which the hydrometer sinks in distilled water be marked 1, the markings on the scale below this point will be greater than 1, and above will be less than 1.

By adjusting the hydrometer so that it will sink about midway on the scale in water, the one instrument may measure specific gravities greater and less than unity; but in order to gain greater sensitiveness it is common to use two instruments, one for liquids denser than water and the other for liquids lighter than water.

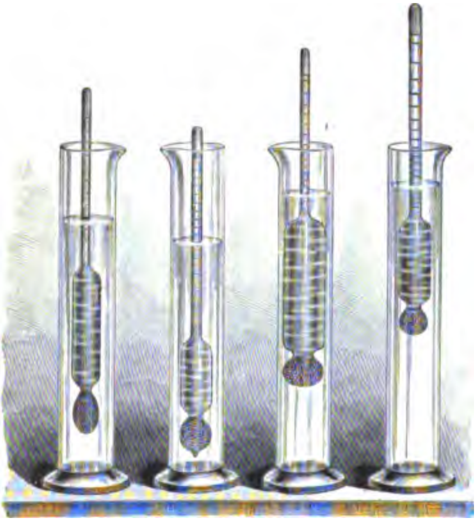

FIG. 58.—Hydrometers of constant weight.

The alcoholmeter is a hydrometer made especially to measure alcohol. The upper end of the scale, marked 100, is the point to which the instrument sinks in pure alcohol. The lower part of the scale, marked 0, is the point to which it sinks in distilled water. The intermediate readings give directly the percentage of alcohol.

The lactometer is a hydrometer graduated with special reference to milk, and is used by official inspectors. Other hydrometers, such as Baumé's, are graduated empirically—that is, without direct reference to specific gravity—and are used in industries where it is desired to keep trade secrets.

In all of the above work it has been assumed that the solids are heavier than water and will not dissolve. In case they are lighter they must be weighted with some solid of known specific gravity and the calculation made accordingly. In case they dissolve in water, another liquid in which they will not dissolve must be used and the necessary correction made.

There is a classic story to the effect that Hiero, Tyrant of Syracuse, having a daintily wrought crown which he suspected not to be of pure gold, sent it to the philosopher Archimedes to test for him. The philosopher was puzzled, for the crown was to be tested without any damage to the clever workmanship. But one day, being in the bath and noticing that his body displaced its own volume of water, it occurred to him that buoyancy would enable him to determine the specific gravity of the crown, and thus he might compare it with pure gold. He sprang out of the water shouting, "Eureka!" (*I have found it.*) He demonstrated that the crown was not gold, and Hiero had the fraudulent craftsman dreadfully punished. Archimedes is celebrated for his researches in buoyancy and specific gravity.

114. **The Specific Gravity of the Human Body.**—There is a great difference in the density of the human body. In fat persons it is less and in thin persons more, but the general average may be stated at .89. All persons ought, therefore, to float; yet many drown each year by taking water into their lungs until the specific gravity rises above 1. It is well known that the bodies of persons who have drowned float again a few days after death. This is due to the inflation of the bodies with gases produced by decomposition.

There are salt lakes where the density of the water is so great that the human body can not sink. The Great Salt Lake in Utah is such a place, and also the Dead Sea in Palestine.

115. **How Iron Ships Float.**—Modern ships are sometimes built of iron or steel, specific gravity 7.75, but being

hollow they displace, without sinking to a very great depth, an amount of water that easily equals their own weight. We sometimes hear that a certain ship is of 10,000 tons burden or displacement. This is the weight of the water which it displaces. This must be the buoyant force of the water and therefore the total weight of ship and cargo. One cubic foot of water weighs about 62.5 pounds. Ten thousand tons of water would fill a tank 400 feet long, 40 feet wide, and 20 feet deep. These dimensions are not so great as some of our largest ocean steamers. By building the ship in water-tight compartments it is practically unsinkable. In case of collision one or more compartments may be broken open and the ship settle considerably, but the displacement of the other compartments will still keep it afloat.

116. **Stability of Floating Bodies.**—There are two points to be considered with reference to the stability of floating bodies. The center of gravity—that is, the point of application of the *downward* force—and the point of application of buoyancy—the *upward* force. This latter must be the center of mass of the submerged portion. The center of gravity and the center of buoyancy must always be in the same vertical line, for otherwise, the forces being equal and parallel, we should have a couple (see page 68), and rotation would bring the two forces into line. When the center of gravity is below the center of buoyancy and in its lowest possible position the equilibrium is stable. When the center of gravity is above the center of buoyancy or is not in its lowest possible position, the equilibrium is unstable and the floating body will capsize if in doing so the center of gravity can assume a lower position. The danger in standing up in a canoe or other light boat is that in doing so the center of gravity of the system is lifted above the center of buoyancy. Yachts have keels of lead projecting far down into the water so as to carry the center of gravity as far below the center of buoyancy as possible.

CHAPTER XV

PRESSURE IN GASES

117. **General Behavior of Gases.**—In their general mechanical behavior, gases differ from liquids only in being sensibly compressible and infinitely expansible. They all exert pressure because they all have weight.

118. **Second Principle.**—(a) *Pressure in gases increases with the depth, but is not proportional to it.* (b) *At any given depth the pressure is equal in all directions.*

119. **The Atmosphere.**—We speak of tumblers, pails, and other hollow vessels as being empty when they contain only air; but a very little examination shows us that the air is a very real substance, and that we must take account of it quite as seriously as of brick and mortar. A tumbler turned upside down and thrust into water is not filled by the water, for the air is already there and excludes the water.

For us the air is an ever-present reality, for we live at the bottom of an aërial ocean, which is estimated to be more than two hundred miles deep. Those of us who live at the sea level are at the bottom of this ocean, where the pressure is greatest. Those who live at places like Denver (about five thousand feet high) or Leadville (about ten thousand feet) are less deep in this ocean of air, and are under considerably less pressure than we are. Men, animals, and plants are no doubt affected to some extent by the variation in atmospheric pressure at different heights upon the earth's surface. It will not do to forget the atmosphere, or leave it out of the count, whether we are dealing with energy and matter, or with animals and plants. It is an ever-present and ever-variable fact.

120. **Weight of Air.**—"Light as air" used to mean light as nothing. Aristotle, the encyclopædia of the ancient world, had hinted that air might have weight; but in general to the early philosophers air and space were about the same thing. Galileo and Guericke showed that air, like all matter, has appreciable weight. If a glass globe holding 1 litre, 1,000 cubic centimetres, be exhausted of air and weighed, then refilled with air and weighed, the difference in weight, if the experiment be made at the sea level and at the temperature of freezing water, will be found to be 1.293 grams. This represents the weight of 1 litre of dry air under normal conditions. Hence 1 centimetre of air weighs .001293 gram, and this number represents the density of air (page 43). The density of water is 773 times as great. In the same way we may find the weight of one litre of hydrogen, .089 gram, or of one litre of oxygen, 1.429 grams, or of one litre of any other gas. These numbers divided by 1,000 will give the density of the gas. It is more common to speak of their specific gravity, however. This is their density divided by the density of air.

$$\frac{.000089}{.001293} = .069 = \text{specific gravity of hydrogen.}$$

$$\frac{.001429}{.001293} = 1.1056 = \text{specific gravity of oxygen.}$$

Or, knowing the weight of one litre of dry air, and the specific gravity of a gas, we can readily calculate the weight of one litre of the gas.

Thus: 1.293 gr. × sp. gr. of gas = wt. of 1 litre of the gas.
1.293 gr. × .069 = .089 = wt. of 1 litre of hydrogen.

A cubic foot of air weighs about 1.28 ounces. Thus, the air in a lecture-room 40 × 50 × 25 feet weighs about two tons. Imagine the air of such a lecture-room moving across the country at the rate of seventy-five miles an hour, as it might in a hurricane. It is easy to conceive that two tons of air moving at such velocity might dislodge some building, or uproot some trees, or pile up sand or snow or sea, or drive furiously a heavy sailing vessel; and the fact that it moves with such momentum impresses us not only that it has velocity but also weight.

121. **The Barometer.**—Over two hundred and fifty years ago (1643) Torricelli, a pupil of Galileo, conceived a plan for measuring the pressure of the atmosphere so simple and direct and so altogether excellent that it has been used ever since. A straight glass tube (Fig. 59), about one metre long and about five millimetres in diameter, is closed at one end and completely filled with mercury. The open end is then closed by the thumb, and the tube inverted. It is thrust under the surface of a bath of mercury and the thumb withdrawn, as soon as all communication with the air is closed off. The mercury in the tube falls a little, and after a few oscillations comes to rest at a point many centimetres above the level of mercury in the bath. We represent this height by *h*. At the sea level, under usual conditions of weather, and at the freezing point, it is seven hundred and sixty millimetres. The simple form, represented in Fig. 60, is much in use. Such an instrument is known as a *barometer* (pressure gauge). Let us consider the forces at work. On the free surface of the

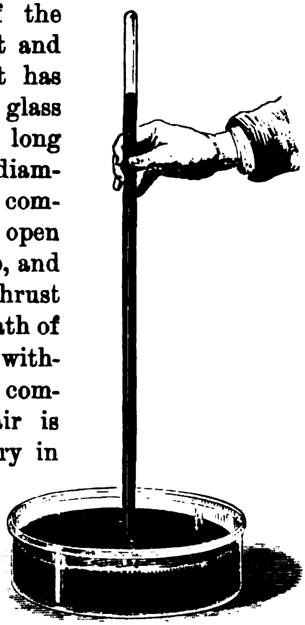
FIG. 59.

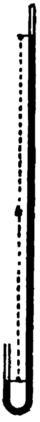
FIG. 60.

mercury there is manifestly the downward pressure of the atmosphere. This is transmitted, and acts upward in the tube at the same level with undiminished intensity. Here it meets a downward force, the weight of a column of mercury of height *h*. As the mercury in the tube stands still, the two forces must be equal. As *h* would be the same, whatever the cross-section of the tube, let us consider it to be 1 sq. cm. The weight of a column of mercury 76 cm. high and 1 sq. cm. in cross-section is manifestly the weight of 76 cubic cm. of mercury. As the density of mercury is 13.596, the weight of 76 cubic cm. must be $76 \times 13.596 = 1033.296$ grams. This, then, is the pressure exerted by the atmosphere on every square centimetre of surface, and is commonly called one atmosphere.

The pressure of the atmosphere is thus expressed as weight. It may be expressed as force by multiplying the result by g, since $F = ma = mg$. $1033.296 \times 980 = 1{,}012{,}630$ dynes (pages 52 and 55).

The barometer is like a pair of weighing balances where liquid pressure upon one scale-pan counterbalances gaseous pressure upon the other scale-pan.

In English units *h*, under normal conditions, is about thirty inches. If we consider the barometer to have a cross-section of one square inch, the atmospheric pressure per square inch must be the weight of thirty cubic inches of mercury, or 14.7 pounds. Hence, it is common to say that the atmospheric pressure is fifteen pounds to the square inch. In one convenient form of barometer, *Fortin's* (Fig. 61), the cistern has a flexible bottom, and a little ivory pointer establishes the level of the mercury. A screw in the lower part of the cistern makes it possible to raise and lower the flexible bottom, and so adjust the level of the mercury to the pointer. This forms the zero of the permanent scale. By means of the sliding vernier at the top of the barometer tube (Fig. 62) the reading may be taken directly and with great accuracy.

Other liquids may be used in a barometer. The special advantage of mercury is that its great density makes the column conveniently short. Its disadvantage is that the variations in h are correspondingly small. In a water barometer we have the reverse conditions, an inconveniently long column, 76 cm. × 13.596 = 1033.296 cm., and large variations in h.

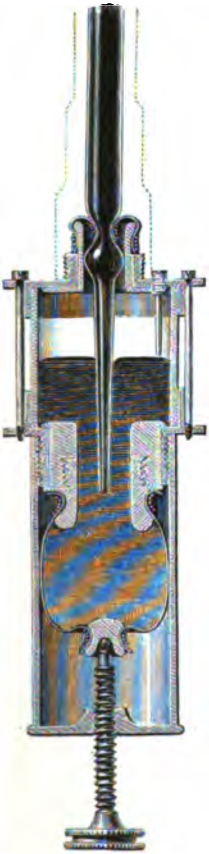

FIG. 61.—Fortin's barometer.

122. **The Aneroid Barometer.**—The mercury barometer is the most accurate form that we can have. It is, however, not conveniently portable, and where observations are to be made on top of a high mountain or other spot of difficult access, the aneroid barometer is often substituted. In this the atmosphere acts against the flexible corrugated metal cover of a sealed box (Fig. 63). The greater the pressure, the more the flexible cover will be forced in. Its motion is transmitted by a system of delicate levers to a light pointer, which moves over the surface of a graduated circle. The reading is made directly in millimetres of mercury, the graduation being effected by comparison with a standard barometer.

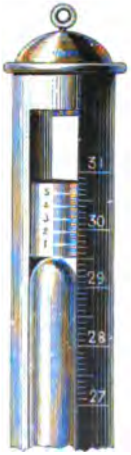

FIG. 62.—Vernier.

123. **Variations in Atmospheric Pressure.**—The pressure of the atmosphere is always changing. The barometer records this change, and serves us in a double capacity. If

the barometer be fixed, it records the change at any one spot; if the barometer be taken to different elevations above the sea, it tells us the elevation by means of the change.

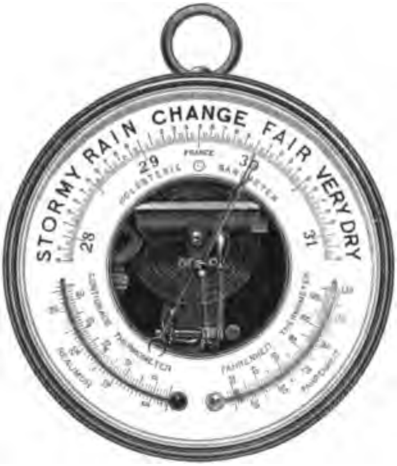

FIG. 63.

First. If the ocean of air covering the earth were allowed to come to rest we should have final equilibrium, when the pressure was exactly the same at the same altitude all over the world. In that case, a fixed barometer would always give the same reading, and, once taken, the barometer would be of no further service. But we all know that the air is far from being at rest. It is, in fact, constantly in motion. The rotation of the earth and the difference of temperature set up currents and counter-currents in this aërial ocean that give us all the phenomena of wind, from gentlest zephyr to fiercest hurricane. But the effort at equilibrium goes on just the same, and the barometer has much to say about our probable weather.

A *low* barometer indicates storm, because it means that air from surrounding regions will rush in to restore equilibrium, and will probably cause precipitation—rain, snow, hail, sleet—according to the season. A *high* or rising barometer means fair weather, because it indicates a flowing away of air from that spot, and consequently freedom from outside influence.

The Weather Bureau at Washington receives daily telegrams from all the observatories throughout the country

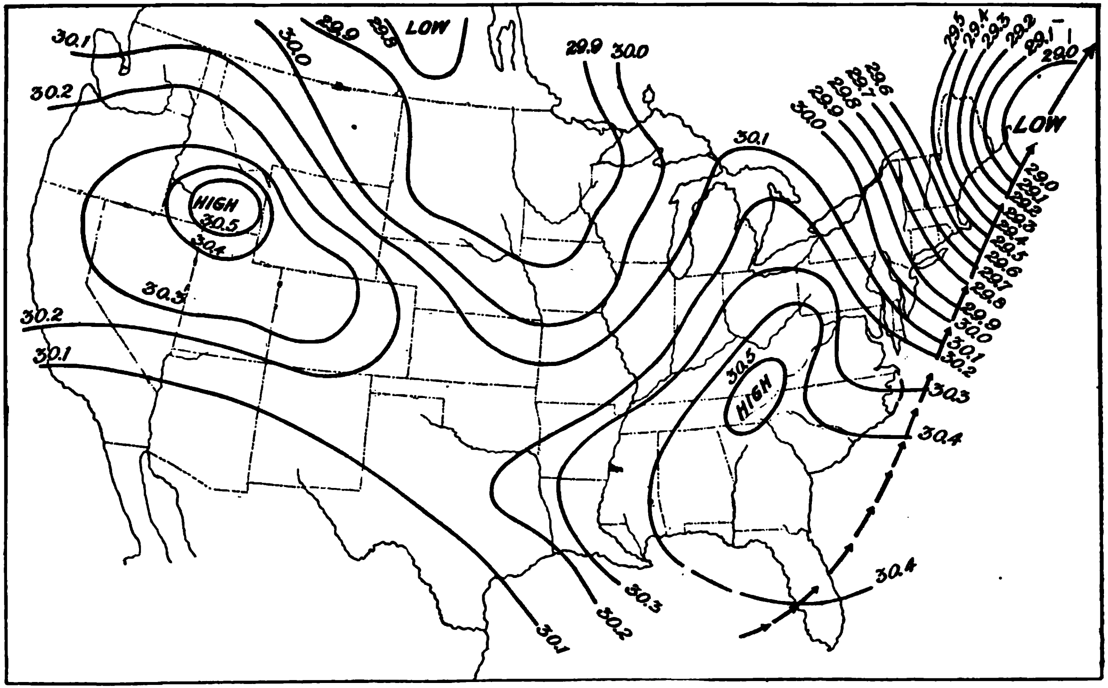

FIG. 64.—Weather Bureau map.

stating the barometer and other climatic conditions. These data are at once put down on the map so that one can see the conditions over the whole country at a glance. Lines joining places of the same pressure are called *isobars.* These lines are found to curve about certain centers. The accompanying weather map (Fig. 64) illustrates the actual conditions of the atmosphere with respect to pressure in all parts of the United States on a certain day and hour.

Secondly. The variations in pressure at any one spot are small compared with its variations when taken to different heights. If the atmosphere were of uniform density throughout, like an ocean of water, it would be about five miles high and the elevations in it would be directly proportional to pressure; but on account of its compressibility and variations in the temperature the density of the atmosphere is very far from uniform, and a somewhat complicated formula must be used to get the exact height. The atmosphere is naturally much denser near the surface of the earth, since it is here under greater pressure. Half the atmosphere is within three and a half miles of the earth, since at that elevation, about 5½ kilometres, the barometer stands at 38 centimetres. For moderate altitudes the fall of h is about 1 centimetre for an ascent of 100 metres.

124. **Boyle's Law.**—On account of the perfect compressibility and elasticity of gases their volume changes with the least change of pressure. Boyle in England and Mariotte on the Continent found that the volume of a gas is inversely proportional to the pressure it supports, or, in other words, that the product of pressure and volume, $p\,v$, is always constant.

$$p\,v = p'\,v' = p''\,v''.$$

This can readily be shown experimentally. For pressures greater than one atmosphere, Figs. 65 and 66 represent convenient forms of apparatus. The latter consists of two short pieces of glass tubing connected by rubber tubing. The lower piece of glass tubing is closed at c. Mercury fills the tubing from *a* to *b*. The arm *a* is lowered until the mercury stands at the same level in both arms. The length of the column of air *b c* is then noted while it is under the pressure of the atmosphere alone. The arm *a* is then raised until the mercury at *a* is, say, thirty inches higher than at *b*. The air *b c* is then under the pressure of two atmospheres, and it will be found to have contracted to one half its original volume. If the difference in level between *a* and *b* is made fifteen inches, the pressure will be three halves of an atmosphere and air will be compressed to two thirds its original volume. If the pressure is made four thirds of an atmosphere, the volume will be reduced to three fourths, etc.

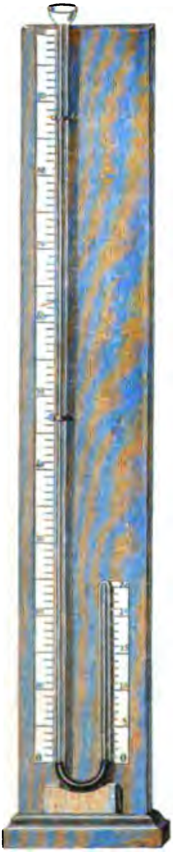

FIG. 65.

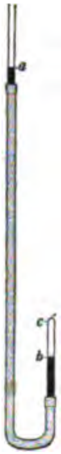

FIG. 66.

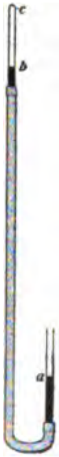

FIG. 67.

For pressure less than an atmosphere, Fig. 67 represents the way the apparatus is used. Suppose *a* is fifteen inches below *b*, then the pressure upon the air *b c* is one atmosphere minus half an atmosphere—i. e., the pressure is reduced to one half and the volume will be increased to 2. If *a* is made twenty inches below *b*, the pressure will be one third and volume 3, etc.

This is Boyle's law, which may be stated in words as follows: If the temperature be constant, the volume of a body of gas varies inversely as the pressure. The law is not absolutely correct, the variation being greatest in case of those gases like ammonia and carbon dioxide that are easily liquefied.

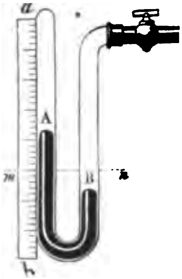

FIG. 68.

125. **Closed Pressure Gauges.**—For many purposes it is desirable to measure the pressure of a gas, as the pressure of steam in a boiler, the pressure of illuminating gas in a main, the pressure of air in the air blast of a furnace, and the like. If the pressure is but slightly in excess of one atmosphere the pressure gauge may be open. The reading is generally given directly in millimetres of mercury. For larger pressures the closed pressure gauge is more convenient (Fig. 68). The pressure is measured by the decrease in the volume of the inclosed air. Such an instrument is practically a balance—on one side the elasticity of the air, on the other side the pressure of the gas.

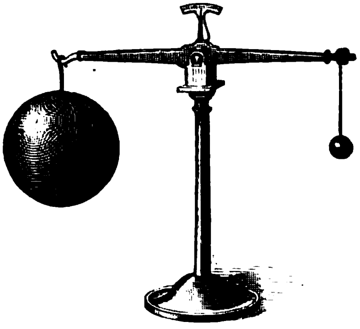

FIG. 69.

126. **Buoyancy of Air.**—It has already been stated that bodies immersed in any fluid, whether liquid or gas, are pressed upward with a force just equal to the weight of the fluid displaced. In the case of air, if the bodies are heavy, the buoyancy is so slight that it is commonly neglected; but in very accurate weighing the weight of an equal volume of air must always be added to the apparent weight of a body, since its real weight is reduced by just that amount. True weight is therefore the equivalent of weighing in a vacuum. This buoyancy can be shown experimentally by a balanced hollow sphere (Fig. 69). When it is placed under the receiver

of an air pump and the air exhausted, the sphere shows itself to be heavier than its counterpoise.

127. **Balloons.**—The principle of aërial buoyancy also makes it possible for us to construct air ships and balloons that will float and even remain at varying heights at our will. If we know the dimensions of a balloon and the gas with which it is filled, we can easily calculate its buoyant force.

Example.—What weight will a spherical balloon 20 metres in diameter and filled with hydrogen gas support at sea level? Let the conditions be normal.

Volume $= \frac{1}{6}\pi D^3 = \frac{1}{6} \times 3.1416 \times (2{,}000)^3 =$
4,188,800,000 cubic centimetres or 4,188,800 litres.
Weight of 1 litre of air = 1.293 grams.
Weight of 1 litre of hydrogen = .089 grams.
Buoyant force of air upon 1 litre of H = 1.204 grams.
Buoyant force of the air upon the balloon =
$4{,}188{,}800 \times 1.204 = 5{,}043{,}315$ grams.
= 5,043.3 kilograms (about 5½ tons).

To find the available uplift we must, of course, subtract the weight of the silk envelope, cordage, car, and other paraphernalia. Those who know how to make H, and how to calculate quantities in chemistry by means of atomic weights, can readily calculate how much Zn would have to be dissolved in acid in order to fill such a balloon.

Volume of balloon = 4,188,800 litres.
Weight of 1 litre of H = .089 grams.
Weight of total H $= 4{,}188{,}800 \times .089 = 252{,}802.2$ grams.

Now for the chemical part: $Zn + H_2SO_4 = ZnSO_4 + 2H$. Each atom of Zn dissolved liberates 2 atoms of H, and 65 grams of Zn will yield 2 grams of H, and hence 32½ times 252,803.2 grams of Zn will be required, or 4,108 kilograms (about 4½ tons). Thus the original question might take this form: How much Zn must be dissolved in acid in order to produce enough H to fill a balloon that is to have a buoyant force of 1,000 kilograms?

It follows from the fact that the air is compressible, that the balloon, if its volume were constant, would displace a greater weight of air at sea level than at an elevation. If we desire the balloon to float near the earth's surface we may load it with bags of sand, and if we desire it to rise to greater heights we throw out these bags of sand. When we desire the balloon to descend we open a valve and let out some of the gas with which it is inflated, thus decreasing its displacement.

PROBLEMS.—1. What will be the weight of one litre of carbonic-acid gas, the specific gravity being 1.53?

2. Which is absolutely the heavier, a pound of feathers or a pound of gold, and why?

3. If a body of gas occupy 1.2 litres, when $h = 760$ millimetres, what will be its volume when $h = 748$ millimetres?

4. A steel cylinder 3 feet high and 16 inches in diameter is filled with oxygen gas. The pressure gauge shows that the gas has a tension of 240 pounds per square inch. How much space would this gas occupy if allowed to escape into the atmosphere under normal conditions?

CHAPTER XVI

TRANSMISSION OF PRESSURE IN FLUIDS

128. **The Transmission of Pressure.**—Chapter XIV dealt with *pressure in liquids*, and Chapter XV with *pressure in gases*. It must not be overlooked that the study of pressure in gases was to a large extent a review or reiteration of the first principle stated in section 108. Gases are separated from liquids in this discussion because they are compressible, while liquids are not. The third principle, which we are about to take up in this chapter, is equally applicable to both liquids and gases, and is merely a more extended discussion of what was first presented in section 109.

When pressure is exerted on a rigid solid the pressure is transmitted in a straight line from the point of application of the pressure to the point of support of the solid. This is very obvious. When pressure is exerted on a fluid precisely the same thing takes place, but—and this is the important matter—where *is* the point of application of the pressure on a fluid, and where *is* the point of support of the fluid? If we can answer these two questions we shall have the main facts about the mechanics of fluids.

First, as to the point of application. This can not be a point at all, since a point would simply penetrate the fluid by pushing its molecules aside, and would exert no pressure whatever. No pressure can be exerted on a fluid except by an extended surface, and only then if the surface be moved against the fluid so rapidly that the fluid has no chance to push by and escape, or by having the surface act against the fluid in a fluid-tight vessel. The first method is used in the blade of an oar, paddle wheel, propeller screw, or rudder, where pressure is exerted against water. In a windmill the same method is applied to the air. Observe that it makes no difference whether the surface is forced against the fluid, as in oar and paddle, or the fluid is forced against the surface, as in rudder and windmill. The second method of getting hold is well illustrated by the pressure of the piston upon the confined air in a bicycle pump.

129. **Third Principle.**—*Pressure exerted upon a fluid (liquid or gas) inclosed in a vessel is transmitted equally in all directions, the total pressure upon the walls of the vessel being proportional to the area.*

A person applies his mouth to one arm of the mercury pressure gauge and finds that he is capable of exerting with the air from his lungs a pressure sufficient to support a column of mercury three inches high—a pressure which we have learned (section 107) to designate as one and a half pounds pressure per square inch; if he now applies his mouth to two pressure gauges at the same time with an effort equal to that used before, he may make each of them register three inches, or one and a half pounds per square inch. In the same manner he may exert pressure upon any number of pressure gauges simultaneously, and find that it is as easy to hold up a hundred columns of mercury as it is to hold up one. There should be no paradoxes in physics. The statement of this third principle has been withheld until now in order that its truth should appear axiomatic rather than paradoxical. Should any one find this principle obscure he is advised to review Chapters XIV and XV.

If a certain definite pressure is exerted upon a gas inclosed in a vessel, one, two, or any number of pressure gauges may be inserted in top, bottom, and sides of that vessel and all will be found to indicate the same pressure.

If the fluid had appreciable weight, as would be the case with a liquid, the pressure gauge would, of course, indicate that in addition to the given external pressure, and they would vary according to the depth of the liquid.

Suppose rubber cloth is tied air-tight over the top of a jelly-cake tin (Fig. 70), the diameter of which is ten inches. A tube is inserted air-tight into the side of the tin; a board is laid on top, and a weight placed upon it. A person who applies his mouth to the tube and exerts a pressure from his lungs of one and a half pounds per square inch may have the novel experience of lifting about 118 pounds by the breath of his mouth. It is, of course, understood that the weight is to be only just started to rise, and not lifted any appreciable distance, in which case the tension of the rubber cloth may be neglected.

FIG. 70.

The applications of the principles of fluid pressure in practical life are very numerous and important. They may be analyzed in the same way as machines (section 98).

Power put in, minus friction = work got out

$$p\,d = w\,s.$$

130. **Hydrostatic Press.**—This depends upon Pascal's principle that fluids transmit pressure equally in all directions, and was one of the first and most famous applications of that principle. If a pressure of 100 kilograms be exerted upon a small piston (Fig. 71) having a cross-section of 1 square centimetre, and if the large piston P have a cross-section of 80 square centimetres, it is clear that the upward pressure exerted on P will be $80 \times 100 = 8{,}000$ kilograms. The hydrostatic press gives us a

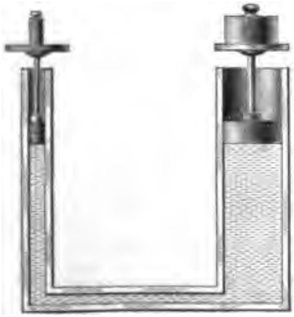

FIG. 71.

means of exerting enormous pressures with comparatively small forces. It must be remembered, however, that the principle of work comes in—that is, virtual velocities, $p\,d = w\,s$, and that what we gain in force we lose in space. In the present example P exerts a pressure eighty times as great as the pressure acting on p, but it only moves through one eightieth of the distance that p does. The press is used in some form in nearly every large engineering and industrial operation. It is also used to compress cotton, hay, and other substances, to extract the oil from seed, and to perform many other useful and Herculean labors.

CHAPTER XVII

APPLICATIONS OF PRINCIPLES OF FLUID PRESSURE

131. **The Density of Milk.**—Cream is lighter than milk; for this reason it floats upon the top of the milk. Skimmed milk is therefore heavier than whole milk, and it is evident that whole milk coming from different cows, and from the same cow at different times, must differ in specific gravity as the proportion of cream varies. The lactometer is an instrument for determining approximately the amount of cream in the milk by taking its specific gravity, which in fairly good milk ought to be about 1.032. It will be noticed that water is also lighter than milk, so that it is possible for the milkman to rob the cream from the milk and then restore it to its proper specific gravity by adding water. This fraud must be detected by the intelligence of the customer acting together with the lactometer.

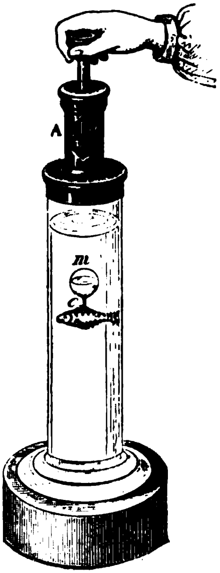

FIG. 72.

132. **The Bottle Imp, or Cartesian Diver.**—Many historic pieces of apparatus which were for years the idols of physical museums, but which have rather fallen into disfavor because they served no better purpose than to mystify pupils, may be made interesting

and properly instructive when used as a means of correlating principles which are thoroughly understood. The bottle imp, or *Cartesian diver* (Fig. 72), always has an air chamber, sometimes concealed, within the body. This chamber contains just enough air to float the object. The chamber communicates with the water outside by a very narrow passage. If any extra pressure is exerted upon the water some of it is forced into the chamber condensing the air. The buoyant force is thus decreased and the object sinks. When the pressure is removed the air expands again, and the object rises.

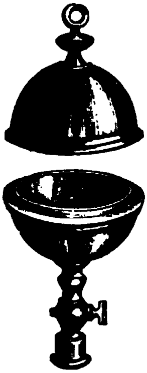

FIG. 73.

133. **Magdeburg Hemispheres.**—The pressure of the air is strikingly illustrated by the apparatus (Fig. 73) invented by Otto von Guericke, burgomaster of Magdeburg. The hemispheres should be made to fit together air-tight by smearing vaseline around the edges. Ordinarily they separate with perfect ease, but when the air has been exhausted from within they are held together by a pressure of fifteen pounds per square inch; and if their diameter is about four inches it will require a pull of nearly two hundred pounds to separate them.

134. **The Relation of Tension and Pressure.**—It is helpful to think of the air in a bottle as a coiled spring (Fig. 74). If a weight of fifteen pounds rests upon the spring its tension is fifteen pounds. By this we mean the force with which it tends to expand. If now the weight be reduced to ten pounds the spring will expand until its tension is ten pounds. If the weight be reduced to five pounds the spring

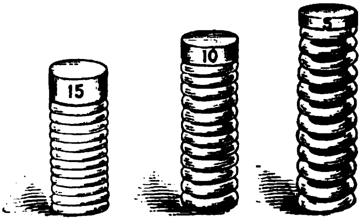

FIG. 74.

will expand until its tension is only five pounds, etc. The tension must always equal the pressure in order that there may be equilibrium. The air acts like this spring, but it differs in that it is indefinitely expansible. We may think of air in a bottle as being condensed in there under a pressure of fifteen pounds per square inch. Its tension or outward push upon the walls of the bottle is thus fifteen pounds per square inch. If the pressure be reduced, one half the air will expand until half of it has been pushed out of the bottle. (See Boyle's Law, 124.) Its tension will then be only seven and a half pounds per square inch, etc.

135. **Bacchus Illustration.**—This relation of tension and pressure is well illustrated by the apparatus which used to be called Bacchus illustration (Fig. 75). The tension of the air in the upper part of the bottle is, say, fifteen pounds per square inch. This would push the water out of the curved tube if the atmospheric pressure from without did not balance it. If now we place this bottle under a receiver and reduce the atmospheric pressure, or if it were carried up in a balloon into reduced atmospheric pressure, the tension of the air within would drive out a stream of water. If by any means the tension of the air within is reduced, or the pressure of the air outside is increased, water passes into the bottle.

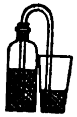

FIG. 75.

136. **"Siphon" Bottles, Fire Extinguishers, Compressed-air Motors, and Explosives.**—It is manifest that the so-called "siphon" bottles depend upon gas compressed within so as to have a much greater tension than fifteen pounds per square inch to drive out the liquid. This gas is carbon dioxide, and the pressure is frequently 140 pounds per square inch. Many kinds of fire extinguishers illustrate this same principle. Some depend upon air compressed within them to throw the liquid upon the fire. Ammonium carbonate dissolved in water makes a very good liquid for this purpose. Others depend upon carbon-

dioxide gas generated at the right moment within the apparatus to supply the tension which shall throw this stream.

Air guns and all the various forms of compressed-air motors operate by the difference between the tension of the air from within and the pressure of the air from without. For example, if a cylinder with the capacity of two cubic feet has forty cubic feet of air compressed within it, its tension, according to Boyle's Law, will be 300 pounds per square inch. This operating against an atmospheric pressure of fifteen pounds per square inch would give a working force of 285 pounds per square inch.

All guns operate by the same principle as air guns—that is, the force which projects the bullet is the tension of greatly compressed gases. The explosives used generate a large volume of gases in a confined space.

137. **Diving Bells and Caissons.**—Diving bells have a tension of air within equal to the pressure of both water and atmosphere from without. The same principle is illustrated in the use of caissons for laying foundations under water. Tunnels are built through the mud under rivers, the workmen operating through holes in a huge steel cylinder, the tension of the air within being made sufficiently great to balance the pressure of mud, water, and atmosphere from without. This balance was so nicely adjusted in the work on the Hudson River Tunnel that the tension of the air within was continually changed to correspond with the varying water pressure due to the rise and fall of the tide in the river.

138. **The Eardrum.**—The inner chamber of the ear, like all other cavities of the body, is filled with air, or gases, having a tension equal to atmospheric pressure. In order that the membrane which is stretched across the tube be free from stress, the volume of the inside air must remain constant, and this can be done only by having its tension vary according to changes of atmospheric pressure. This

is accomplished by the Eustachian tube, which communicates between the throat and the inner chamber of the ear. When atmospheric pressure increases, air is forced in through this fleshy tube until the tension within equals the pressure from without. When atmospheric pressure decreases, air passes out by the same channel. "A cold in the head" sometimes clogs this channel; then we experience disagreeable sensations about the ears, caused by the sagging in or bulging out of the membrane of the ear, due to inequality between the tension within and atmospheric pressure without.

Persons who are about to pass into a caisson are advised to try to force air out of their lungs while holding the nose and mouth closed. Why? Try it under ordinary atmospheric conditions, and explain the physical cause of the peculiar sensation in the ear. Persons about to come out of a caisson are advised to close the mouth and hold the nose shut, and perform the act of swallowing. Why? Try this also under ordinary atmospheric conditions, and explain the physical cause of the peculiar sensation in the ear. It will be a more striking experiment if you swallow a mouthful of water or of food. Did you ever have a similar sensation during eating, while suffering from a "cold in the head"?

139. **The Physics of Respiration.**—A similar adjustment of tension to pressure is made in the act of breathing. By the contraction of certain muscles we are able to force the ribs upward and outward, and to depress the diaphragm. This enlargement of the chest cavity would produce a reduced tension of the gases within, if atmospheric pressure did not maintain the balance by pushing more air in, and thus inflating the lungs. By the contraction of certain other muscles we are able to contract the chest cavity. This would result in increased tension of the gases within, if they did not flow out at a rate to maintain the balance.

140. **How Atmospheric Pressure upon the Human Body is sustained.**—From this discussion it is manifest that the story is only half told when one speaks of the enormous pressure of thousands of pounds which the atmosphere exerts upon the human body. The other half, which should be coupled with this statement, is that all the tissues of the body are permeated by gases which have a tension exactly equal and opposite to the atmospheric pressure; and that while the communication between all bodily cavities is not as free as in the cases of lungs and eardrum, there is a somewhat slower communication by the process of osmose, by which the balance between tension from within and pressure from without is always maintained. As might be expected, sudden and great changes in pressure, as one who goes up in a balloon experiences, occasion painful sensations before the internal tension has had time to adjust itself. The tissues of the body in ordinary circumstances are under no more stress from atmospheric pressure than a very thin glass flask or a delicate tissue-paper bag whose mouths are open. Manifestly these are not enduring great stress from atmospheric pressure.

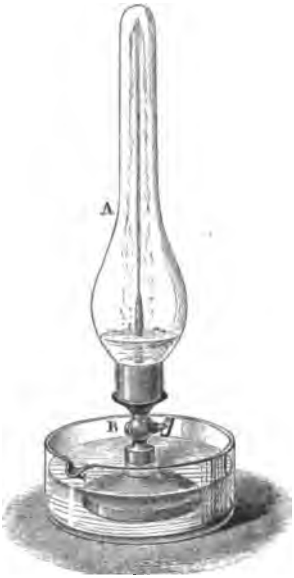

Fig. 76.

141. **"The Fountain in Vacuo."**—The apparatus illustrated in Fig. 76 shows again the relation of tension and pressure. If the tension of the air or any other gas inside the bottle be reduced by the action of a pump, or the contraction of the gas by cold, or the absorption of some of the gas by a substance introduced for that purpose, at-

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mospheric pressure from without will force the water in the lower vessel to rise until the volume of the gas inside shall be reduced so that its tension may equal the pressure upon it. Manifestly the water which enters the bottle is very nearly a measure of the amount of air removed.

142. **Pumps.**—It goes without saying that pumps have to deal with both classes of fluids—liquids and gases. We may take water pumps and air pumps as the two types. Both involve the same principle, but there are differences in form and construction that deserve notice. The most common form of water pump is the so-called cucumber pump, in which the pipe leading down into the well is simply a hollow length of cucumber wood. The rod attached to the pump handle has a piston at its lower end provided with a valve (*a*) opening upward (Fig. 77). At a given point somewhat below the lowest possible position of the moving piston, there is a valve (*b*) also capable of opening in an upward direction only. The valves are the essential part about such a pump. The action is very simple. When the pump is at rest, both valves *a* and *b* are closed by their own weight. Imagine a downstroke of the pump rod. The chamber *A* is filled with air, which opens the valve *a* and escapes. Now picture an upstroke. The valve *a* closes, and as the piston rises, increasing the volume of the space in the chamber between the two valves, the tension of the air in this chamber is reduced. Atmospheric pressure, being no longer balanced, presses to enter. The only entrance into the chamber from without

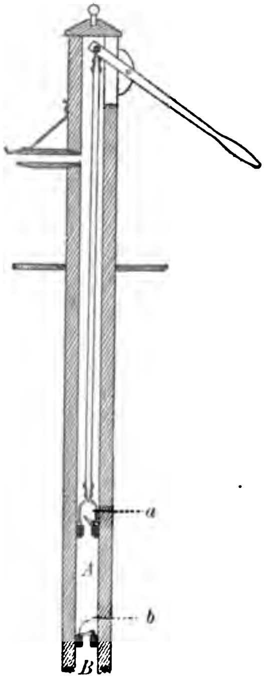

FIG. 77.—Cucumber pump.

is by the lower gateway *b*, and if the lower end of the pump tube dips into water the air will drive the water before it so long as its weight is less than the pressure to be exerted by the air. When enough air from the lower tube has been pushed up through *b* to make the tension in the chamber equal to the atmospheric pressure, minus the pressure of the column of water which now stands part way up the lower tube, equilibrium is again restored. The next down- and up-strokes repeat the operation until all the air in *B* is exhausted, and water begins to pass through the valves. The water that passes *a* is lifted bodily by the upgoing piston and escapes from the spout. It is plain that *B* must not exceed about thirty feet in length, or the pressure of the atmosphere will not support the column of water, and all our pumping would be in vain.

These cucumber pumps are used in every village and on nearly every farm. The pump has many other forms, but the principle remains the same. The pump is frequently made of iron, and in large operations is run by steam.

143. **"Force" Pump.**—The water thrown out by such a pump as has been described above falls in intermittent streams. The more rapidly the pump is operated, the less noticeable the inequality of the stream. It is possible, however, to slightly alter the construction of the pump, and make the stream of water reasonably constant. This is accomplished in the so-called force pump (Fig. 78). As before, there are two valves; one (*b*) opening upward into the chamber below the piston, and the other (*a*) opening out of the chamber into the delivery pipe. This

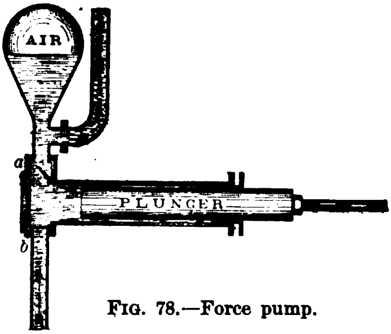

FIG. 78.—Force pump.

latter pipe does not, however, simply terminate in a spout. It has connected with it an air chamber. Picture an up-stroke: *b* opens and water rushes up into the chamber below the piston. Now, a down-stroke: *b* closes and *a* opens. Water passes to the air chamber, and thence out of the delivery tube. The end of the delivery tube is constricted by a nozzle. This offers resistance to the flow of the liquid, and as a result the air in the air chamber is compressed, and continues to force water out of the delivery tube during the next up-stroke of the piston rod. The next down-stroke again opens *a* and forces water into the air chamber and into the delivery tube beyond. This secures a continuous and fairly constant stream of water.

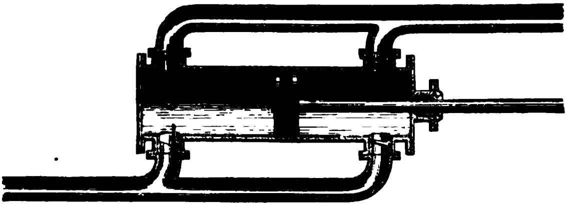

FIG. 79.—Double-acting pump.

Double Pumps.—It is usual in the steam pumps to have the piston double-acting. In this case the piston is commonly horizontal, as shown in Fig. 79, and at each stroke of the piston water is drawn into one end of the piston

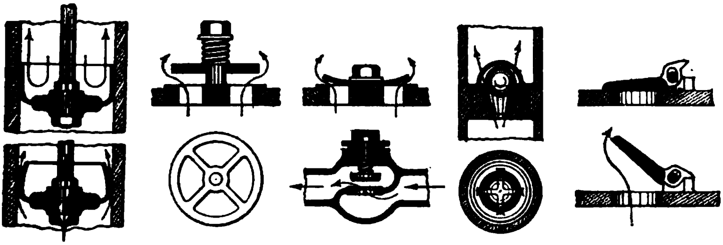

FIG. 79*a*.—Typical valves.

chamber and forced out at the other end. In this way the stream of water is continuous.

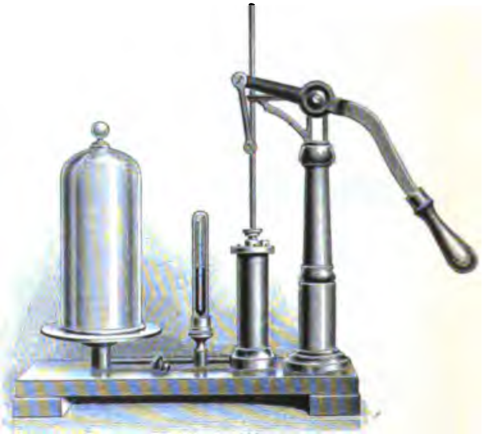

FIG. 80.—Air pump.

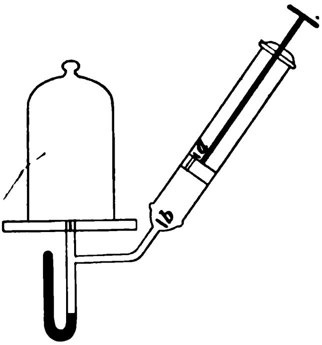

FIG. 81.—Air pump.

144. **Air Pumps.**—The air pump serves a double purpose —to exhaust the air in a given receiver, and to furnish a steady stream of air, just as the force pump does of water. The term air pump is usually reserved for instruments of the first class, while air compressor and blowing engine are used for the latter. In the ordinary air pump (Figs. 80 and 81) the valves are just the same as those in the water pump. The receiver to be pumped out is commonly a glass bell jar resting on a carefully ground brass plate, from the center of which a tube passes to the cylinder of the pump. The valve (*b*) at the end of this tube opens into the cylinder. A second valve (*a*), often for convenience located in the piston itself, opens from the cylinder into the atmosphere. At every up-stroke the air in the receiver expands into the cylinder; at every down-stroke *b* closes, and the air in the cylinder passes through *a* into the outer atmosphere. It is impossible in this way to get a

perfect vacuum in the receiver, for finally the residual air has not tension enough to open the valve *b*. It is also impossible, theoretically, since any process which removes a fractional part of air then in the receiver must always leave a residue of air. A small pressure gauge constructed on the same principle as the manometer shows exactly the amount of residual pressure—usually only a few millimetres of mercury. For most purposes the air pump is perfect enough, and allows many interesting experiments—such as removing the air from the Magdeburg hemispheres, from the apparatus known as the "Fountain in Vacuo," etc.

145. **The Mercury Air Pump** (Fig. 82).—This is constructed on the principle of the barometer, and what we get is really a Torricellian vacuum. As the pellets of mercury fall down the tube they form little air-tight pistons; but gravity being a constantly accelerating force tends to make these pellets go faster and faster. Consequently, they get separated by small vacuous spaces, and as these pass the opening *a* into the receiver, the air in the receiver expands and fills these spaces. In this way the air in the receiver becomes more and more rarefied, and as there are no valves to be opened the exhaustion can be carried to a high degree of perfection. The residual pressure is shown at any time by subtracting the height of the column of mercury, *b c*, from the barometric height. If these columns were equal it would indicate a perfect vacuum.

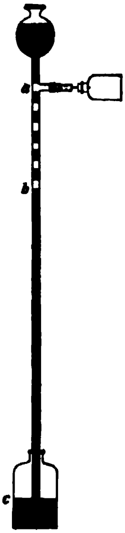

FIG. 82.—Mercury pump.

146. **The Water Exhaust** (Fig. 83).—In the laboratory it often happens that we want an exhaust at hand without ourselves doing the pumping. Running water permits such an exhaust with the least inconvenience. The principle is similar to that of the mercury pump, but we give the water as

great velocity as possible by making it escape through a tapering nozzle. In this way the water carries part of the air away with it, and produces a partial vacuum.

147. **Air Compressors and Blowing Engines.**—By reversing the valves in the usual type of air pump, we have a pump for compressing air (Fig. 84). Each down-stroke of the piston closes the valve *a*, compresses the air in the cylinder, opens the valve *b*, and forces the air into the compressed-air receiver. It is manifest that this simple instrument may serve at least three purposes: 1. It may be used to exhaust the receiver *A*. 2. It may be used to condense gas in the receiver *B*. 3. It may be used for transferring gas from one receiver to another.

There are many modifications of the pump and many practical applications, such as the bicycle pump, pump for the compressed-air brake in use on all modern trains, for the compressed illuminating gas used in many railway cars, for testing the gas pipes in our houses, for producing sprays in medical treatment, and so on. The most important application is in the powerful blowing engines used at all blast furnaces.

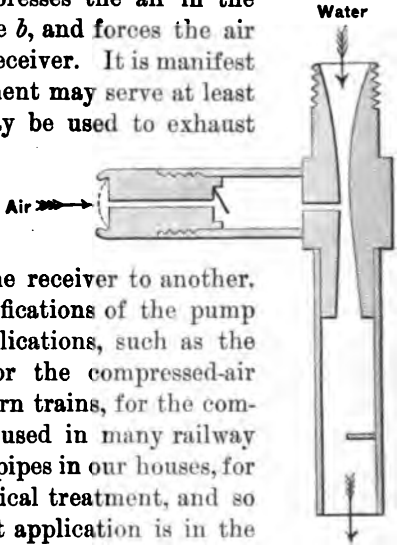

FIG. 83.—Water exhaust.

148. **Siphons.**—The siphon is a very simple device for transferring fluids from one level to a lower level over an intervening obstacle. Siphons depend for their action upon two principles—the pressure of the atmosphere and the tendency of all fluids to seek their own level. They will not work in a vacuum, and they will not raise fluids to a height greater than that of a barometer filled with the fluid in question—that is, 76 centimetres in the case of mercury, or 1,033 centimetres in the case of water.

Let us analyze the simplest form of siphon, a U-shaped tube of glass with one leg longer than the other. Suppose it to be in operation, transferring water from the level *b* to the level *c* over the intervening obstacle, represented by the wall of the vessel (Fig. 85). The atmosphere acts on the surface of water in both vessels with an equal pressure, which we may represent as *h*. There is also at the level *c* in the lower vessel a downward pressure of a column of water of height *a c*, and further, at the level *b*, in the upper vessel, a downward pressure of a column of water, *a b*. The downward pressure in the longer leg of the siphon therefore exceeds the downward pressure in the shorter leg by the weight of a column of water, *b c*. Water consequently flows over the arch of the siphon and into the lower vessel, and continues to flow either until the upper vessel is emptied or the level of water is the same in both vessels. Apparently the atmosphere has nothing to do with it, but imagine for a moment the absence of atmosphere. The only force being gravity, the water would flow down in both legs of the siphon, and we should simply have a vacuum in the tube. Or, imagine an atmosphere, and make *a b* 40 feet. Suppose the siphon completely filled with water and free to act. At once the water would separate in the arch of the siphon and sink to a height of about 34 feet in each of the legs.

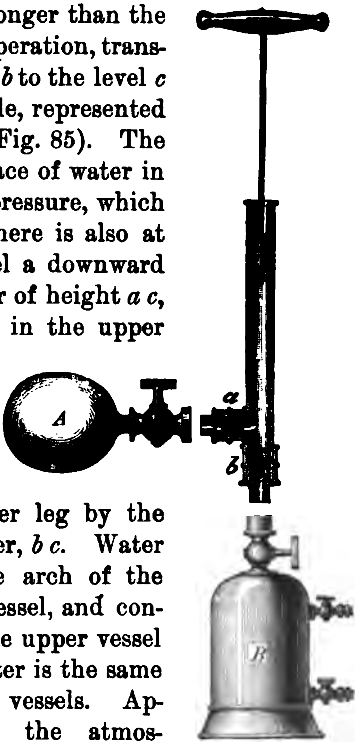

FIG. 84.—Compressor.

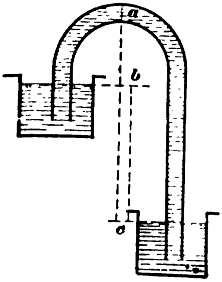

FIG. 85.—Siphon.

There would be a barometric vacuum in the arch and no flow of water whatever.

A piece of rubber hose completely filled with water and dipping under the surface of water in two vessels at different levels often serves as a convenient siphon, and is somewhat easier to fill and start than a rigid glass tube.

Aspirating Siphon (Fig. 86).—The difficulty of filling and starting the plain glass siphon is so considerable, and especially in the case of sulphuric acid and other chemicals not to be freely handled, that a modification of the instrument has been devised known as the aspirating siphon. In this a second tube leads upward from near the bottom of the longer leg, and after swelling into a little bulb near the top is turned at right angles and formed into a mouthpiece. To start the siphon the shorter leg is dipped into the liquid in the upper vessel and the longer leg is closed either by the thumb, if the liquid be harmless, or by a stopcock if harmful. The mouth is then applied to the mouthpiece and the air sucked out of the two tubes. The liquid rushes over and fills both tubes. The bulb is intended to show the operator more plainly when the liquid is getting dangerously near his mouth. The suction is stopped and the longer leg of the siphon is opened. The liquid flows over as in the plain siphon, and

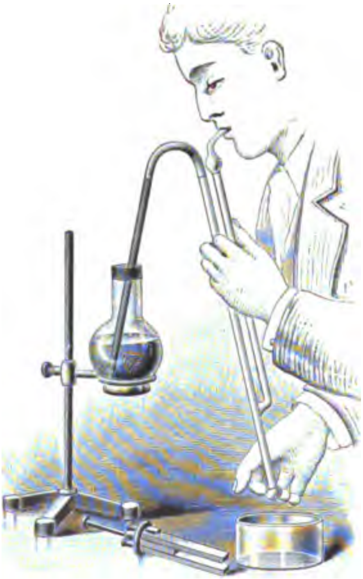
FIG. 86.—Aspirating siphon.

the aspirator has no further influence. Great care must be taken not to get acid or other dangerous chemicals into the mouth.

Fountain Siphon (Fig. 87).—The siphon may be given a multitude of forms, and may be very ingeniously modified. A very pretty form is the fountain siphon. A round-bottom Florence flask is fitted with a doubly perforated rubber stopper, and is supported in an inverted position. A straight glass tube passes through one of the perforations (preferably in the middle of the stopper) and ends inside the flask in a fine jet. A second tube passes through the other perforation, and with the addition of a rubber hose forms the long leg of the siphon. It is easy to start the fountain by having a little water in the flask before it is stoppered. When the flask is inverted the water runs out the open tube into the hose, and at once the fountain begins to play. If the difference of level in the two vessels is considerable the water rises in a single thread and strikes against the walls of the flask with no little force.

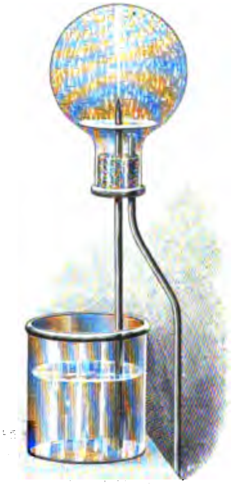

FIG. 87.—Fountain siphon.

149. **Siphoning Gases.**—It is quite as possible to siphon gases as liquids. If the gases are heavier than air we do it right side up; if lighter than air we do it upside down. Let us take two large battery jars (Fig. 88) and fill the upper one with carbon-dioxide gas (CO_2), sp. gr. = 1.56. This gas can easily be made by placing fragments of marble ($CaCO_3$) in a gas-generating flask with a little water, and adding hydrochloric acid (HCl) through the thistle tube. CO_2 is given off copiously, and by means of a rubber hose may be con-

ducted into the upper jar. The CO_2 is quite invisible, but it extinguishes a flame at once, and so a burning match will tell us when the jar is full. A lighted candle is placed in the lower jar. By means of the aspirating siphon, or a bit of rubber tubing, a stream of CO_2 is now made to pass over from the upper jar. The gas stream is, of course, invisible, but it will be noticed that the candle burns less and less brightly, and finally flickers and goes quite out.

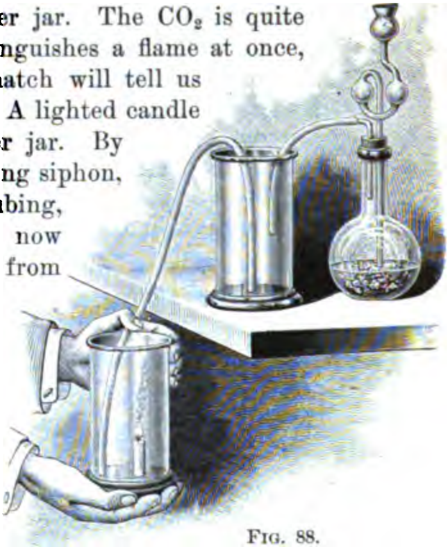

FIG. 88.

In the case of light gases like hydrogen (H), sp. gr. = .069, both the gas jars and the siphon are inverted, and the H passes from the lower to the higher jar. At the beginning of the experiment the lower jar is filled with H, the upper jar with air. At the end the H is in the upper jar. It, too, is invisible, but its presence can be shown by applying the open end of the jar to a flame. A considerable explosion announces a mixture of H and air.

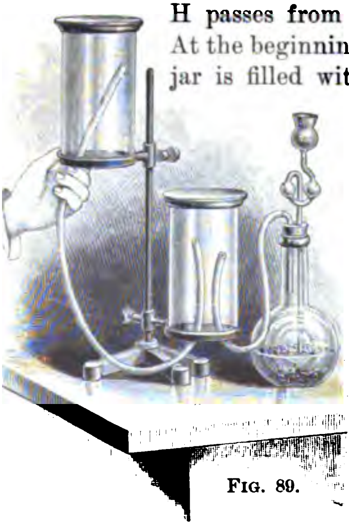

FIG. 89.

150. **Hero's Fountain** (Fig. 90).—This bit of classical apparatus, invented by Hero of Alexandria, 120 B. C., deserves notice as an

interesting case of transmitted pressures. In starting the experiment *M* should be nearly full and *N* nearly empty of water. There must also be some water in the pool *D*. The column of water from the pool to the lower globe exerts a pressure upon the air in that globe which is transmitted through the tube to the air in the upper globe and forces the water out in a jet. It is sometimes used for cologne fountains, and the liquid can be used over and over again by pouring it back from *N* to *M* each time it runs down. A cheaper form is shown in Fig. 91. It can be made out of three bottles and a little tubing.

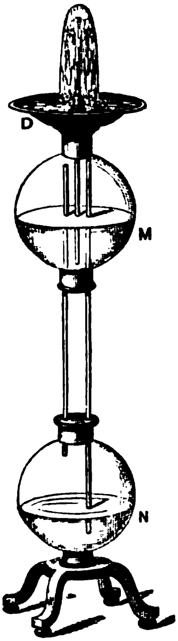

FIG. 90.—Hero's fountain.

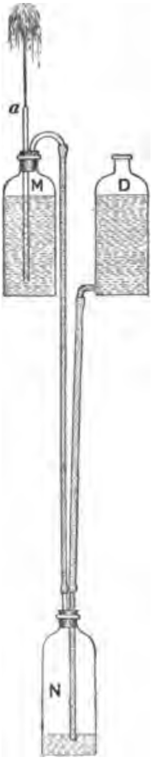

FIG. 91.

151. **Tension inside the Barometer Tube.** — If the space in the upper end of the barometer is a vacuum there is no tension there, and it is manifest that the walls of the tube must sustain in that part the whole atmospheric pressure of fifteen pounds per square inch. If this portion of the tube were made of rubber, its sides would collapse under the pressure. How is it with other portions of the tube? In the lower end of the tube, at the level of the mercury in the cistern, the outward pressure of the column of thirty inches of mercury must be equal to the inward pressure of the atmosphere. Here the tube might be made of the thinnest rubber and neither expand outward nor con-

tract inward. Halfway up the tube the pressure from without is still that of an atmosphere, while the pressure from within is that of half an atmosphere—fifteen inches of mercury. So it appears that while the pressure from without is fifteen pounds per square inch throughout the whole length of the tube, the pressure from within varies all the way from fifteen pounds at the lower end to zero at the upper end. A water barometer may be made of rubber tubing with a closed glass tube in the upper end, but it needs to be the thick-walled Bunsen pressure tubing to prevent its sides from collapsing. If a pin-prick is made anywhere along the side of this tube, water does not leak out, but air leaks in. A water barometer must not be expected to stand thirteen and six tenths as high as the mercury barometer, although from consideration of specific gravity alone we might expect that. The tension of water vapor in the upper end of the tube depresses the column somewhat.

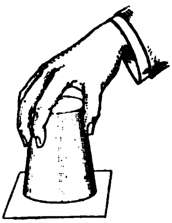

FIG. 92.

152. The Inverted Tumbler of Water.—From the above discussion of tension inside the barometer tube we naturally find an explanation for the time-honored experiment of the inverted tumbler of water (Fig. 92). The upward pressure of the air upon the paper which covers the mouth of the tumbler is fifteen pounds per square inch, while the downward pressure is merely the weight of the water so long as no air gets in to produce an internal tension. The experiment may even be performed by putting mosquito netting over a wide-mouth bottle full of water, and it need not be tied or held in place; atmospheric pressure will do that. Medicine droppers, students' lamps, fountain ink wells, fountain sponge

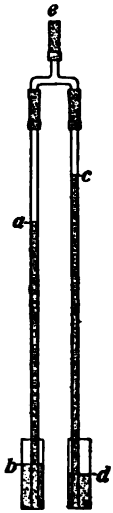

FIG. 93.

cups, etc., all hold their liquids because atmospheric pressure from without is greater than the tension from within.

153. **The Specific Gravity of Liquids measured by balancing them against Atmospheric Pressure.**—Fig. 93 illustrates a simple way of finding the specific gravity of liquids. One tube dips into a vial of water and the other into a vial of liquid whose specific gravity is to be found. When a person applies his mouth to the tube *e* and reduces a little the tension of the air in the tubes, the atmospheric pressure forces each liquid up its respective tube, and by comparing the length of the columns it is possible to obtain the relative weights. It is manifest that the column of liquid *c d* must have the same weight as the column of water *a b*, since the weight of each column of liquid must be equal to the pressure of the air from without minus the tension within. From this we should find that a column of water eight inches long balances a column of alcohol about ten inches long.

154. **Fluids in Motion.**—It is to be noted that in all our study of fluids thus far we have considered them in a state of rest, and thus the elements of friction and momentum have not complicated our problems. In the apparatus illustrated in Fig. 94 the water in the tube *stands* at the same level as the water in the reservoir, but Fig. 95 illustrates the fact that the water will not flow in a fountain to the same level. Friction in the tube, the resistance of the air, and the interference of the falling drops of water, all act to prevent this. If the water in a system of city water works were absolutely at rest it would

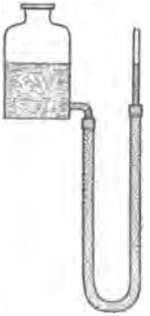

FIG. 94.

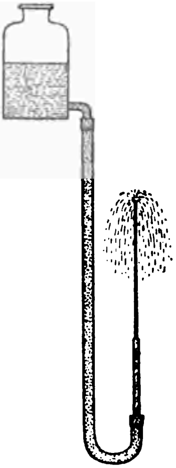

FIG. 95.

rise in a house pipe as high as the level of the water in the reservoir; but the fact that the water is flowing continually through the pipes to supply so many faucets during the daytime prevents its rising to the upper stories of many of the houses in large cities, although the reservoir may be far above them. At night when less water is used it may rise even to tanks upon the roofs of these same houses.

Water wheels and windmills are run by the momentum of the moving fluids rather than the pressure of those fluids at rest. The word *hydrostatic* refers to fluids at rest; *hydraulic* refers to fluids in motion.

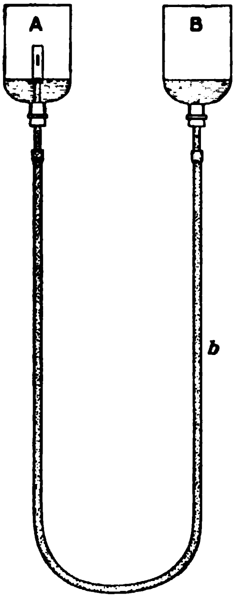

FIG. 96.—Principle of hydraulic ram.

155. **The Hydraulic Ram.** — This instrument depends upon the momentum of running water. The principle of it may be illustrated by a very simple piece of apparatus.

Let the two reservoirs *A* and *B* (Fig. 96) be connected by a rubber tube. The end of the tube in *A* is supplied with a valve which prevents the fluid returning from *A*. If we seize the rubber tube at *b* and raise it a few inches and then let it fall with a sudden jerk, the momentum of the moving column of water will push a small amount of water up through the valve in *A*. By repeating this movement several times *B* may be emptied of its water and carried above its level in *A*. This is the idea which underlies the hydraulic ram, whereby water is made to flow from a source upon a hillside, first down into a valley, and then to a house farther up the hillside than the source. In order to accomplish this a portion of the water must run to waste. It is the energy of this portion of the water that does the work of lifting the other portions of the water to the house. A diagram will make the mechanism plain.

D (Fig. 97) is the spring from which water is to be carried through a pipe *C* to a house which is higher than the spring. If the valve *A* should remain closed, water would stand at the same level in *C* as at *D*; but the valve *A* is made heavy enough to sink in quiet water. As soon as it sinks, however, the water ceases to be quiet, and rushes out through the orifice above with such a rush as to toss the valve shut again with a smart thump. When the flow of the water is thus suddenly stopped at *A* its momentum forces open the valve *b*, and some of it passes in to compress the air in the chamber *B*. At the rebound of this air the valve *b* closes and some water is forced higher up the tube *C* leading to the house. As soon as the water in the apparatus becomes quiet the valve *A* sinks again, and the events just described are repeated.

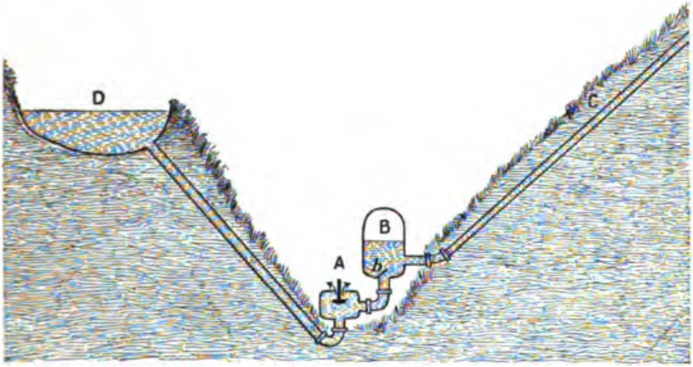

FIG. 97.—Diagram of hydraulic ram.

HEAT

CHAPTER XVIII.—How Heat is produced

156. General Definition of Heat.
157. Heat produced by Friction.
158. Heat produced by Percussion.
159. Heat produced by Pressure. Figs. 98, 99, and 100.
160. Heat produced by Chemical Action.
161. Other Sources of Heat.

CHAPTER XIX.—Some Effects of Heat

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CHAPTER XVIII

HOW HEAT IS PRODUCED

156. **General Definition of Heat.**—In studying *heat*, we study only a particular form of energy—molecular motion—and all that we have learned about motion in general is applicable to the motion of molecules. Like all forms of energy, heat represents two elements—matter and motion. It is a measurable quantity, and the measurement may be made with respect to the two aspects of energy studied in mechanics—that is, to the degree or intensity of motion and to the total amount of motion or momentum. By the degree or rate of motion we mean speed or velocity, measured in centimetres per second. This measurement is independent of the amount of matter. In the case of heat we can not measure the velocity directly in centimetres. The motion, being molecular, is quite invisible. It consists of a to-and-fro motion, a vibration, and not of a plain and simple change of position. We can only measure the intensity of the molecular motion by means of its effects, and this we do with a thermometer (section 167).

The total amount of motion, or momentum, is the product of mass and velocity, or $m v$.

In heat the amount is measured in the same way. It is the degree of heat motion multiplied by the mass of the matter in motion. But here, again, the measurement must be conventional, since the degree of heat motion can not be measured in absolute units. The measurement of heat quantities is treated under the head of *Calorimetry* (Chapter XXI).

The term *heat* is used in two very different senses. First, the physical sense, the molecular motion of a body; and, second, the physiological sense, the sensation produced in us by contact with a hot body. We shall use it always in the physical sense, to represent the thermal condition of a body. We can not judge of this accurately by means of our own sensations, for hot and cold are merely relative terms. When we come in from the cold a moderately warm room seems *hot* to us, and when we pass from an overheated room into a moderately warm one it feels *cold* to us.

Neither can we judge of the relative heat of two bodies by simply touching them, for the sensation produced does not depend alone upon the degree of heat in the bodies touched, but also upon the relative speed with which they give up or absorb heat when brought in contact with the hand. Thus, pieces of iron and of wood may be equally hot, but to the hand the iron will seem much the hotter, because it gives up its heat more readily than the wood. The two may be equally cold, but not to the touch; the iron will seem much the colder, because it takes away heat more rapidly from the hand. On a cold morning we instinctively avoid handling all metal objects, but we pick up wood or cloth without hesitation, although they are all of the same, or nearly the same, temperature.

Until the end of the eighteenth century it had been believed by many eminent philosophers, among whom was Sir Isaac Newton, that heat was a very subtle fluid that more or less completely filled the pores of all substances, and could be transferred from one to another, much as water flows from one vessel to a communicating one, and only comes to rest when the level is the same in both. In the closing years of that century two celebrated experiments were made, that showed once for all that heat is not a substance, but is simply a motion of the molecules.

An American, Benjamin Thompson, afterward Count Rumford, had charge of the boring of cannon in the arsenal at Munich, and, observing that great heat was produced, he became interested to investigate the matter. He found that by immersing the cannon in water and by purposely using a very blunt boring tool he could easily produce enough heat to make the water boil. He rightly reasoned that what could be produced in such unlimited quantity by the expenditure of mechanical energy must itself be a form of energy. He even established a rough relation between the amount of mechanical energy that disappeared and the amount of heat that took its place. This was in 1798. The year following, Sir Humphry Davy showed that two pieces of ice rubbed together below the freezing point could be melted by the heat of friction.

At the present time no one seriously doubts that heat is a mode of motion—that is, a form of energy; but it took the first third or even the first half of the nineteenth century to establish the doctrine on firm scientific grounds. The final victory was gained by the experiments establishing the exact quantitative relation between heat and mechanical energy—that is, the mechanical equivalent of heat—work that will always be associated with the name of the English scientist Joule. The doctrine has been theoretically worked out by such men as Clausius, Helmholtz, Tait, and Maxwell, and made popular by Tyndall and other able experimenters.

Heat, from the standpoint of physics, is a vibration of molecules—the greater the amplitude of vibration the more intense the heat. From the standpoint of physiology it is an irritation of certain nerve endings by appropriate means—as, for example, the pelting of these vibrating molecules of matter against the skin.

Since heat is a form of energy—one variety of molecular motion—it can only be produced by the transformation of some other form of energy into heat. This is accomplished so readily that heat has been called the currency, or medium of exchange, in the realm of energy. We may therefore expect to find that there are a great variety of ways of producing heat.

157. **Heat produced by Friction.**—When mechanical motion is interrupted in any way, as in friction, we have the movement of the whole transformed into a movement of the parts—that is, into heat. We do this when we rub our hands together on a cold morning. A coin or other bit of metal rubbed against a flannel blanket or against our coat sleeve becomes uncomfortably warm. It is quite possible to measure the relation between mechanical motion and heat—the quantity of heat that corresponds to a given amount of mechanical energy. In this way we may get the thermal equivalent of motion, or the mechanical equivalent of heat.

It is a familiar fact that machinery warms up while running. It has already been said that the work done by any machine is never fully equivalent to the power applied to it. The loss is due to friction, and the heat which warms up the machine while in motion is the equivalent of this apparently lost energy. Anything which will reduce friction should therefore diminish this loss. Hence we oil the machine when we desire it to perform work rather than produce heat.

The relation between heat and work constitutes a distinct branch of physical science called *thermodynamics*. It expresses the quantitative relation between two important forms of energy, and is an application of the doctrine of the conservation of energy.

158. **Heat produced by Percussion.**—When a bullet strikes a target its mass motion is converted into molecular motion, or heat. When we hammer a nail, both the hammer and the nail become hot; the pile driver and the pile become hot in the same manner. The earth is moving through space, around the sun, at the rate of about nineteen miles per second. Could it be stopped, its motion would be

transformed into heat, and this would be sufficient to vaporize the entire earth. Indeed, that is precisely what is happening to hundreds of meteors which daily fall into the earth's atmosphere. In 1854 Sir William Thomson concluded that the heat of the sun was chiefly due to the percussion of meteors which fall upon it.

159. **Heat produced by Pressure.**—When gases are condensed by a pump, temperature rises (Fig. 98). When they are allowed to expand again they return to their original temperature. If, while a gas is under pressure, the heat is conducted off and the pressure is then removed, the expansion will cause the temperature to fall as far below the original temperature as it was raised above that by pressure. This is well illustrated in certain ice machines, where the heat produced by pressure is removed by running water, and the cold which is produced by the sudden expansion of the gases is sufficient to freeze water. (See also 216.)

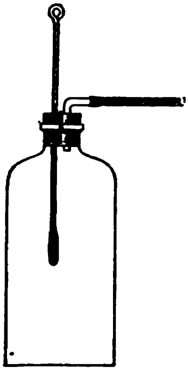

FIG. 98.—Heat by pressure.

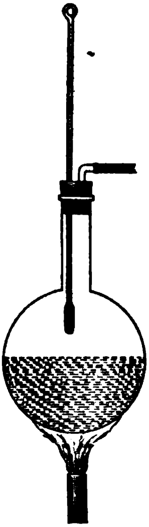

FIG. 99.—Temperature of steam under pressure.

It is pretty generally known that water boils at 212° Fahrenheit. Without extra pressure its temperature can not be raised above that point. We may, however, raise it to any desired temperature by putting its steam under sufficiently great pressure (Fig. 99). Because of great pressure, steam in a locomotive boiler is much hotter than 212°. When this steam issues in a jet, however, the sudden expansion reduces its temperature, so that it is only lukewarm (Fig. 100).

The internal heat of the earth may be due to the pressure of its mass. The rise in temperature is about one degree Fahrenheit for every fifty or sixty feet of descent, varying much in different localities. It must be understood that motion must result from pressure in order to produce heat—that is, the earth must be still contracting under its own weight if heat is being now produced. But the internal heat which was produced in former centuries by this contraction has very great difficulty in getting away from the earth. It has been estimated that so little of it reaches the surface as to effect a rise in temperature of only one thirty-sixth of a degree. So likewise the heat of the sun may be produced chiefly by the action of gravitation in pulling its particles of matter nearer together. Von Helmholtz calculated that all the sun's heat for a year would be produced by the contraction of thirty-eight metres in its radius. If it continues to give out heat at the present rate for four million years, it will then be contracted to half its present diameter.

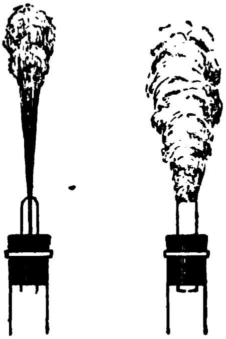

FIG. 100.

The total heat sent to the earth annually from the sun would be capable of melting a sheet of ice fifty-four metres thick, extending over the whole surface of the globe. The earth, being distant about ninety-two million miles from the sun, receives only the one-twenty-one-hundred-millionth part of the entire amount of heat which the sun sends forth on all sides. How the sun's heat is transmitted through space from the sun to the earth, and what transformations it passes through after it reaches the earth, will be discussed in other chapters.

160. **Heat produced by Chemical Action.**—The process of ordinary burning, or combustion, is the union of a sub-

stance with oxygen. Burning, combustion, and oxidation are nearly synonymous terms. The process, however rapid, as in the case of combustion, or slow, as in the case of the rusting of a metal, is always accompanied by the production of a definite amount of heat, which bears a fixed ratio to the amount of chemical action.

The familiar instance of the slaking of lime with water is an illustration of the production of heat by chemical action. Both the lime and the water may be very cold, but when they are mixed their atoms clash together in forming a new compound, and the molecules of the new substance are left in a state of vibration so intense as to cause the water to boil, or even to set wood on fire. Storehouses of lime frequently take fire by rain leaking in upon the lime. Ships loaded with lime are in similar danger. Compost heaps get very warm by reason of the slow chemical decomposition that is going on in them. Piles of green grass, new grain, new hay, new flour, cotton with seed in it, or oily cotton waste, all produce heat for the same reason. Animal heat is produced in like manner. Most of our foods are particularly liable to chemical change; indeed, their value as foods depends upon this characteristic. Animal heat is due chiefly to the breaking down of these compounds in the body.

161. **Other Sources of Heat.**—Electricity is one of the latest sources of heat to be utilized by man. We shall see, when we come to this subject, that whenever a current of electricity meets resistance in its passage, heat is produced. This is sufficient to cook with in the electric stove. Our electric cars are warmed in winter by turning electric energy into heat. Heat is produced from the electric current for welding metals and for fusing the most refractory substances. We shall study this matter more in detail under Electricity.

HEAT

CHAPTER XVIII.—How Heat is produced

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along one principal axis, and may even contract at right angles to this direction. This is the case with Iceland spar.

There are variations in the coefficients of expansion at different positions on the thermometer scale, the coefficient increasing slowly with the temperature. The values given in the table are, however, sufficiently accurate for all practical uses.

166. **Expansion of Liquids.**—Since liquids assume the form of the containing vessel, we measure only the ratio of their increase of volume to that of temperature—that is, their coefficient of volume expansion. Since the containing vessel also changes its volume with change of temperature, all determinations of the expansion of liquids must take this into account. In general, the change of volume is very small. The coefficient rises with the temperature. Water and mercury are the two liquids whose coefficients of volume expansion are of the largest importance. Water presents the curious case of a liquid which does not expand uniformly with the application of heat. A body of water at the freezing point—32° on our ordinary thermometers—on being heated, contracts in volume until it reaches 39°. It then begins to expand, and at 46° has the same volume as at 32°. Beyond this point the expansion proceeds continuously until the boiling point, 212°, is reached, and the water passes into steam. Thirty-nine degrees is therefore known as the point of maximum density of water.

This irregularity in the behavior of water has the utmost significance in the economy of Nature. Bodies of water, such as ponds and lakes, cool at the surface. The upper layers in growing cold also grow heavy, and sink to the bottom. This process continues until the whole body of water has a temperature of 39°. When this point is reached a further loss of heat makes the surface layers lighter as well as colder, and they consequently remain on top. When they reach 32° ice forms and shuts off the under water from any further large loss of heat. As both ice and water are poor conductors, the lower strata of water remain at 39°, and the water life is preserved. If water continued to grow heavier down to 32°, the ice would form at the bottom of all bodies of water, and the hottest of summer suns would hardly suffice to melt it.

The ordinary thermometer is an illustration of the expansion of liquids by heat. Mercury and alcohol expand by heat with sufficient regularity so that we use them to measure rise and fall in temperature.

167. **Measurement of Temperature by the Expansion of Mercury in the Thermometer.**—All ordinary temperatures are measured by means of a well-known instrument—the *thermometer*. This depends for its action upon the effect of heat in making fluids expand. Alcohol was formerly used, and for low temperatures is still used, but mercury has been substituted for the alcohol in nearly all instruments for everyday use. As the temperature rises, mercury expands, but the increase of volume is so slight that, unless we employ some special device for rendering the expansion visible, we should hardly be the wiser. This special device is very simple. We have a glass bulb capable of holding an appreciable amount of mercury, and provided with a fine capillary tube as its only outlet. In this way we have a considerable body of mer-

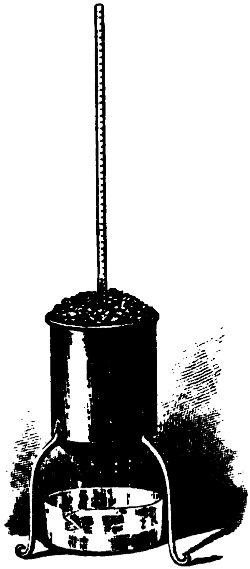

FIG. 102.

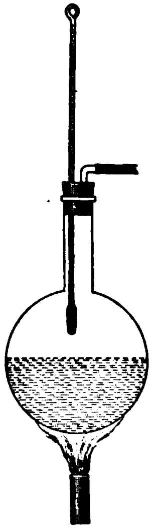

FIG. 103.

cury to expand and contract, but any change in its volume, however slight, makes a very noticeable change in the length of the column of mercury in the capillary tube. Heat also expands the glass bulb, giving it greater capacity, so that the first effect of heating a thermometer is to make the column of mercury sink; but as soon as the mercury also becomes heated, the column of mercury rises, and quite enough for our purpose, since the increased volume of mercury is greater than the increased capacity of the bulb. What we really measure is their difference. The coefficient of volume expansion for mercury is .0001817, and for glass .0000254. The difference between these coefficients, .0001563, represents the apparent expansion of mercury in glass.

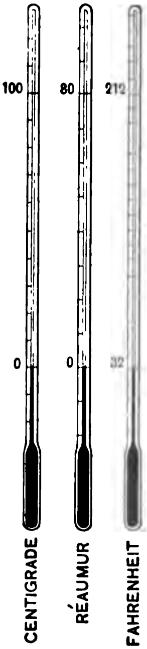

Fig. 104.

Pure water, under a pressure of 760 millimetres of mercury, always freezes and boils at the same temperatures, and so we take these as fixed points of temperature. Figs. 102 and 103 show how these points are found when the thermometer is made.

168. **Centigrade, Réaumur, and Fahrenheit Scales.**—There are unfortunately three different scales of temperature used in civilized countries.

Centigrade Scale.—In this the freezing point of water is called 0°, and the boiling point 100°. The varying temperature of liquid water is thus expressed in one hundred steps, hence the name. This scale was suggested by Celsius, a Swedish scientist, and is used in all scientific work, because of all the scales it is the most rational and convenient. It is also in popular use in France and in the Romance countries generally.

Réaumur Scale.—The freezing point of water in this scale is also called 0°, but the boiling point is marked 80°, and the degrees are therefore larger than in the centigrade scale. It was devised by Réaumur, of France, and has nothing to commend it. Curiously, it is in popular use in Germany and Switzerland.

Fahrenheit Scale.—This is the least admirable of the three. The freezing point is marked 32°, and the boiling point 212°, thus making 180° between the two points. The zero of the scale is therefore 32° below freezing, and is the point that was erroneously supposed to mark the greatest artificial cold producible. This scale is unfortunately the one in common use in the United States, in Great Britain, and in all English-speaking countries. It was devised by Fahrenheit, a German philosopher.

Not one of these scales is used in the country where it originated.

In nearly all German towns there is a public bathing place, where university professors and college students and schoolboys go in warm weather for a daily swim. In some of the places the temperature of the water in degrees Réaumur is posted up each day, so that one may decide for or against a plunge. In the same way the regulations in German art galleries state in terms of Réaumur the allowable variation in temperature.

169. Conversion of One Scale into Another.

1. *Fahrenheit into Centigrade.*—To change any Fahrenheit reading into centigrade, we must first subtract 32°, in order that both readings may count from the same starting point, the freezing point of water. The remainder is then multiplied by $\frac{5}{9}$, since 180° F. = 100° C. Putting this into a compact formula, we have

$$C. = \frac{5}{9}(F. - 32) \qquad (1)$$

Illustrations: Suppose the Fahrenheit reading was 212° (boiling point in F.), then $C. = \frac{5}{9}(212 - 32) = \frac{5}{9}(180) = 100°$ (boiling point in C.).

2. *Centigrade into Fahrenheit.*—In this case we multiply the C. reading by $\frac{9}{5}$, since 100° C. = 180° F., and then add 32,

or $$\text{F.} = \tfrac{9}{5}\,\text{C.} + 32 \qquad (2)$$

Suppose C. = 100°, then $\text{F.} = \tfrac{9}{5}\,100 + 32 = 180 + 32 = 212°$. By making C. = F. in either (1) or (2) we can find the point where both scales have the same reading. Thus:

$$\begin{aligned} \text{F.} &= \tfrac{9}{5}\,\text{F.} + 32 \\ 5\,\text{F.} &= 9\,\text{F.} + 160° \\ 4\,\text{F.} &= -\,160° \\ \text{F.} &= -\,40° = \text{C.} \end{aligned}$$

3. *Réaumur and Fahrenheit.*—In the same way by using $\tfrac{4}{9}$ and $\tfrac{9}{4}$, since 180° F. = 80° R., we may turn R. and F. about

$$\text{R.} = \tfrac{4}{9}\,(\text{F.} - 32) \qquad (3)$$

$$\text{F.} = \tfrac{9}{4}\,\text{R.} + 32 \qquad (4)$$

4. *Centigrade and Réaumur.*—Since 100° C. = 80° R., we have $\text{C} = \tfrac{5}{4}\,\text{R.}$, and $\text{R.} = \tfrac{4}{5}\,\text{C.}$ (5)

170. **Self-recording Thermometers.**—It is sometimes desirable to have an instrument which will record either its own

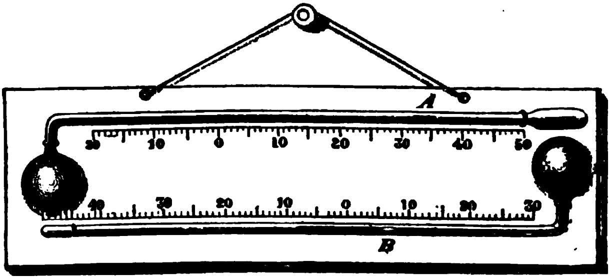

FIG. 105.—Maximum and minimum thermometers.

extremes or its whole variation. The maximum and minimum thermometer does the former, and Draper's the latter. In the first, two thermometer tubes are mounted horizontally on the same scale board. The maximum thermometer has a small indicator, usually a bit of glass, inside the tube, which the expanding mercury pushes in front of it, but fails to pull back when it retreats itself. In this way we have a record of the highest temperature reached. The minimum thermometer is filled with colored alcohol, and carries a little rider inside the fluid, which is so arranged that it will retreat with the alcohol, but offers too much friction when going in the other direction to advance with the alcohol. In this way we have a record of the lowest temperature reached. Such instruments are often used in greenhouses and other places where a narrow range of temperature is necessary for success.

In meteorological stations a more complete record is wanted. In Draper's self-recording thermometer a pointer, moved by the expansion and contraction of metallic bars, traces its own movements on cards prepared for the purpose and made to rotate back of the pointer by means of clockwork. Or the fluctuations of a column of mercury may directly photograph themselves on a roll of slowly moving sensitive paper passing back of them.

171. **Expansion of Gases—Correction of Volume for Temperature.**—We have in gases the most perfect example of expansion and contraction. A cubic foot of any gas measured in winter may expand in summer so as to occupy 170 cubic inches more than a foot. We have already found, from a study of Boyle's law (124), that the measured volume of a gas must be corrected for pressure. It is evident, from what we have learned of the effects of heat, that the measured volume of gas must also be corrected for temperature. It was a French physicist, Charles, who in 1787 first pointed out the law for the relation of volume of a gas to changes of temperature. The volume coefficients for different gases vary slightly, but in general may be stated to be .003663, or $\frac{1}{273}$ of their volume at zero centigrade. That is, gas which would measure a cubic foot at 0° C. would measure at 27° C., the temperature of a rather warm summer day (what would it be on Fahrenheit scale?), 1 cubic foot $+ 27 \times .003663$ cubic feet, or 170 cubic inches more than a cubic foot. If the volume V is given of any gas at 0° C., and we are required to calculate what its volume would be at a given temperature t higher than zero, we multiply V

by 1 + .003663 *t*. If we are required to calculate what its volume would be at a given temperature below zero we multiply *V* by 1 — .003663 *t*. If the volume is given at a temperature above zero, and we are required to calculate what it would be at zero, we divide *V* by 1 +.003663 *t*. If the volume is given at a temperature below zero, and we are required to calculate what it would be at zero, we divide *V* by 1—.003663 *t*.

172. **The Air Thermometer.**—The coefficient of volume expansion for air was found by Gay-Lussac by means of a thermometer with a very large bulb. This was filled with dry air, which was separated from the outside atmosphere by a little pellet of mercury in the tube. Knowing the capacity of the bulb and the diameter of the tube, the percentage increase of volume on heating the air through any given range of temperature could readily be calculated. The same instrument may be used as a thermometer.

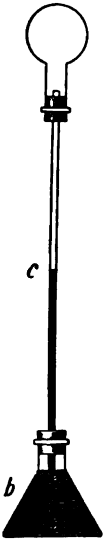

FIG. 106.

If the tube be made of some difficultly fusible material, such as hard porcelain, the air thermometer serves as an excellent instrument for measuring very high temperatures.

173. **Pyrometers.**—As mercury boils at 350° C., and glass speedily softens, the ordinary mercury thermometer can not be used to determine high temperatures. We use here a special class of instruments known as *pyrometers* (fire measures), which depend for their action upon the expansion of air; the expansion of metal bars; the melting of alloys of known melting points; the softening of fire clays; or the variable electric resistance in a platinum conductor, due to change in the temperature. In general the resistance of the metals increases with heat, and consequently the current passing through the conductor becomes weaker the higher the temperature. By

measuring the current with a galvanometer we can measure the heat.

174. **Range of Temperature.**—The lowest temperature so far reached is probably −258° C. (what would this be on Fahrenheit scale?), obtained by the evaporation of solid hydrogen. The highest is probably that of the electric arc, which is estimated to be about 3,500° C. Higher and lower temperatures than these are entirely conceivable, and undoubtedly exist in other parts of the universe, but they are quite outside the range of human experience.

175. **Relation of Temperature to Animal and Vegetable Life.**—Human life exists within rather narrow ranges of temperature, about − 60° F. and + 120° F., and none of us care to endure either of these extremes for any great length of time.

Warm-blooded animals keep a constant bodily temperature, however much the temperature may vary about them. For example, the temperature of the internal organs of a human body must be kept at about 98° F., summer and winter, without change. How this is accomplished will be learned later. Some birds keep a constant temperature of 110° F. The temperature constant varies among different types of warm-blooded animals. Birds and mammals (animals whose young are fed by the mother's milk) are warm-blooded. All other animals are variable in temperature, and their temperature varies as that of their surroundings. They are sluggish as the temperature falls, and more or less active as it rises.

The distribution of plants and animals over the globe appears to be controlled by temperature, so that we have certain kinds of plants and animals peculiar to the tropics, certain other kinds peculiar to the temperate zone, and still other kinds peculiar to the frigid zones. All three kinds of temperature zones may be found upon the slope of a single mountain, each to a limited degree supplied with its appropriate plants and animals.

176. **Heat determines the State of a Substance.**—A gas may apparently be expanded indefinitely, and so may take any increase of temperature without changing its state. Not so with solids and liquids. The heat may be increased to a given point, called respectively the fusing and the boiling point, but beyond this any further increase of heat shows itself by liquefaction and vaporization.

177. **Fusion.**—All solids heated to a sufficient temperature will melt. We can prove this by direct experiment for most solids; and for others, such as carbon, we believe it to be true. Some solids pass directly from a solid to a liquid state, as ice, while others pass through an intermediate pasty condition. The latter appears to be the result of a change in the molecular structure, and has not yet been clearly explained. This pasty condition is important practically, since it allows the process of welding. Two pieces of wrought iron heated to a white heat may be joined together into practically one piece by appropriate hammering.

Sulphur behaves very oddly. Heated at 114.5°, it melts to a thin, straw-colored liquid. At from 200° to 250° the liquid takes on a rich reddish-brown color and becomes so pasty that the test-tube may be turned upside down without loss. Heated still further, the pasty mass again becomes perfectly liquid, grows darker in color, and finally boils at 448.4° and may be distilled. Or if poured into cold water and suddenly cooled, it for a time has the appearance of crude rubber.

The following laws of fusion apply only to substances which show a sharp, distinct melting point:

1. The fusing temperature, under constant pressure, is always the same for the same substance.

2. The temperature during fusion remains constant until the whole substance is melted.

TABLE OF MELTING POINTS.

Mercury	– 39°	Zinc	412°
Ice	0°	Antimony	432°
Butter and lard	33°	Aluminium	600°
Phosphorus	44°	Bronze	900°
Potassium	63°	Silver	954°
Wax	65°	Gold	1045°
Sodium	95°	Copper	1054°
Sulphur	110°	Cast iron	1150°
Tin	230°	Steel	1350°
Bismuth	262°	Wrought iron	1550°
Lead	326°	Platinum	1775°

178. **Change of Volume due to Fusion.**—Nearly all solids increase in volume when they melt, so that as liquids they are less dense, and consequently any unfused portions sink to the bottom. With cast iron, water, and antimony the very opposite is the case. They expand at the point of solidifying, making room for the crystals which form. This force of crystallization is immeasurably great, and, as we saw in section 164, is leveling mountains. As a result of expansion, these solids are less dense and float on their corresponding liquids. Antimony is added to lead in type metal so as to make it expand on solidifying, and fill out all the fine lines of the mold. For the same reason iron makes fine castings and may be fashioned into delicate patterns in stove castings and the like. Metals which do not thus expand are made to receive impressions by stamping them with dies. Ice, as we all know, floats on water. It has a density of only .92, and consequently floats with .08 of its bulk out of water. The giant icebergs seen in northern waters have 11½ times as much ice under water as above.

179. **Change of Fusing Point under Pressure.**—The change of volume that takes place on fusion makes it easy to understand why pressure should change the fusing temperature. Where a solid expands on fusing, pressure increases the amount of work to be done, and hences raises the

fusing point; but where the solid contracts on melting, pressure diminishes the amount of work to be done, and so lowers the fusing point.

180. **Effect of Alloys upon Fusing Point.**—In general, mixtures of two or more solids melt at a temperature lower than their average fusing point, and sometimes less than the fusing point of any one of them. Thus an alloy containing two parts bismuth and one part each of lead and tin melts at from 95° to 98° C. A bar of this alloy held in a jet of steam melts and drops off like butter.

181. **Vaporization.**—Liquids pass to the state of vapor by *evaporation* and *boiling*. Evaporation takes place at the surface only, and proceeds at all temperatures. In boiling, the formation of vapor takes place throughout the mass of the liquid, and only occurs at a definite temperature, which varies with the pressure and the nature of the liquid, but is constant for any given liquid under the same pressure.

182. **Five Factors of Evaporation.**—The evaporation of liquids depends upon five factors:

1. Temperature of liquid.
2. Surface exposed.
3. Pressure.
4. Amount of vapor already in the atmosphere.
5. Renewal of fresh atmosphere.

A moment's reflection will show this to be the case. The hotter the liquid, the more motion will its little particles have, and the more able will they be to detach themselves from their neighbors and go off into space. Evaporation, being a surface phenomenon, takes place in larger measure the larger the surface exposed.

In the chemical laboratory, where we often have occasion to evaporate solutions, we satisfy these two conditions of temperature and surface by using evaporating dishes—shallow little porcelain dishes which may be heated over a Bunsen burner. Where we wish the temperature not to exceed 100° C., we put the dish on a water bath. The same principles are utilized in drying fruit and other products by spreading them out in the sun.

When a liquid evaporates, its vapor has to make way against the overlying atmosphere. Consequently, the smaller the pressure, the less work to be done. Where a high temperature is undesirable, evaporation is now generally carried on in vacuum pans. Our best dried fruits, condensed milk, sugar sirups, etc., are evaporated in this way.

The amount of vapor already in the atmosphere determines the rate of evaporation, because, as we shall see in the next paragraph, a given space can only take up a given amount of vapor. For the same reason a renewal of atmosphere furthers evaporation. The weekly wash is hung out in the open air to dry, utilizing the heat of the sun, the surface of the garments, and the renewal of air by the wind. In dry climates, as in Colorado, one's collar never "wilts" however hot the weather, since the skin always remains dry, the perspiration evaporating as soon as formed.

183. **The Evaporation of Solids.**—By the term evaporation we mean, in general, the passage of a liquid to a gaseous condition. But we have also apparently the changing of solids to gases without passing through the liquid state. Thus snow and ice pass directly into a vapor without the visible formation of moisture when the weather is very dry, even though the temperature may be below the freezing point. Wet clothes hung out upon the line in such weather freeze stiff, but the ice will nevertheless disappear from them in a few hours. Often after a little rain in winter it clears off cold and windy. The moisture upon the sidewalk freezes to a thin glade of ice. A dry wind is blowing, and the temperature is falling all the time, but in a few hours all the ice disappears. In the same way certain volatile solids, such as camphor and ammonium-carbonate, are greedily taken up by the atmosphere. Under the influence of heat other solids, such as iodine and arsenic, pass directly

into the condition of vapor, and condense as solids again when sufficiently cooled, a process which we distinguish as *sublimation*, the condensed products being called *sublimates.* But in all these cases we are forced to imagine that the solids passed, if only momentarily, through the condition of liquid before it reaches the gaseous state, since our experience obliges us to conceive of these states as continuous.

184. **Vapors.**—The amount of evaporation that may take place when a liquid is exposed to a given space is almost independent of the amount of other gases and vapors present in that space—a condition which is commonly summed up by saying that to vapors all space is empty. Under given conditions of temperature and pressure, a given space can only contain a certain amount of a vapor. When this maximum amount is present, the vapor is said to be *saturated.* Below this point the vapor is said to be unsaturated. There is no hard-and-fast line between gases and vapors. The term gas is usually applied to those bodies, like oxygen, hydrogen, and nitrogen, that may be liquefied only under very high pressure and at very low temperature, while the term vapor is reserved for the gaseous state of those bodies, such as water, ether, and alcohol, which under ordinary conditions exist as liquids.

185. **Critical Temperature.**—The greater instrumental facilities that have been brought about by the mechanical progress of recent years have made many remarkable experiments possible. Especially has it enabled us to study the behavior of gases under great pressure. The old distinction of the "permanent gases" has been broken down completely, since every one of them—oxygen, hydrogen, nitrogen, the atmosphere itself—has been reduced to the liquid and even to the solid state. But the temperature must always be taken into account. These experiments have all been conducted at very low temperatures, under conditions therefore which rob the gases of a large part of

their molecular energy. It has been found, for example, that carbonic-acid gas (CO_2), which can readily be liquefied under a pressure of a few atmospheres, can not be liquefied at all if the temperature be above 31° C. Below this temperature, under pressure, the substance becomes a liquid; 31° C. is therefore spoken of as the *critical* temperature for carbon dioxide. It is probable that all gases have such a critical temperature, above which they can not by any amount of pressure be liquefied.

186. **Boiling.**—With increasing temperature, vapors exert an increasing pressure. As soon as this pressure becomes equal to the surrounding atmospheric pressure, the process of boiling takes place, which, as we have seen, is simply the formation of vapor throughout the liquid. If water be heated in a glass flask, the heat being applied, of course, to the bottom of the flask, it will be noticed that the first bubbles produced at the bottom of the water collapse before they reach the surface. This produces the well-known "singing" which is familiar to every watcher of the teakettle. In spite of the rapid currents, the upper layers of water are colder than those below, and so condense the rising bubbles. When all the water is boiling hot, the bubbles reach the surface, and the water boils freely.

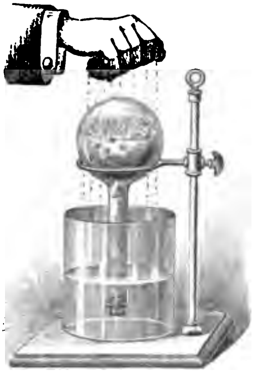

FIG. 107.

After the water has been boiling for some time we shall have all the air driven out of the flask, and only vapor of water occupying the space above the water. If, now, the flask be tightly corked and inverted in a stand over a suitable trough, we may make the water boil again, and quite tempestuously, by pouring *cold* water over the outside of the flask. This result is ordinarily so unexpected that it was early named the "culinary paradox," but in reality it is very easily explained. The cold water chills the flask, and so condenses the vapor of water inside. This greatly reduces the pressure, and consequently the boiling point. Though now below 100°, the water in the flask is still highly heated. The cold water can not, of course, heat the water in the flask up to the ordinary boiling point, but it can and does bring the boiling point down to the temperature of the water.

187. **Laws of Boiling and Table of Boiling Points.**

1. Under a given pressure, every liquid has a definite boiling point.

2. When the boiling point is reached, the temperature remains constant, until the liquid is completely vaporized.

3. The pressure of the vapor given off during boiling is equal to the atmospheric pressure.

TABLE OF BOILING POINTS.

Water	100°	Sulphuric acid	325°
Alcohol	79°	Mercury	353°
Ether	37°	Sulphur	440°
Spirits of turpentine	130°	Phosphorus	290°

188. **Changes in the Boiling Point.**—The boiling point is so characteristic that it is often used, particularly in organic chemistry, to determine whether we have to deal with a single liquid or a mixture. The same principle is made use of in fractional distillation. By keeping the temperature constant, the liquids which distill over will be mainly those boiling at or under that temperature. Or we may allow the temperature to rise at will, and collect the vapors given off within certain limits, such as 80° to 85°, 85° to 90°, etc. This process is used in separating the lighter constituents—benzine, naphtha, etc.—from the heavier oils in crude petroleum. Any change in the composition of a liquid at once changes its boiling point. Pure water alone boils at 100° C. If mixed with alcohol, the boiling point is lowered. If there

are any salts in solution, the boiling point is raised. Common salt may be dissolved in water so as to raise the boiling point to 102°, saltpeter to 116°, potassium carbonate to 135°, and calcium chloride to 179°.

The range in boiling points is very great. Liquefied gases boil at many degrees, even hundreds of degrees below zero, as liquid oxygen, at −180° C. Light liquids boil below 100°, as alcohol at 78°, and benzine at 80°. Heavy liquids boil at higher temperatures, as mercury at 350°.

But the greatest change in the boiling point comes from variations in the pressure. This is but natural, since boiling takes place when the vapor pressure equals the atmospheric pressure. Water boils at 0°, when the pressure is reduced to almost nothing. At places much above the sea, water boils at so low a temperature as to introduce inconveniences into the kitchen. Eggs and vegetables boiled in such water are not sufficiently cooked. Devices are used to increase the boiling point by either adding some salt to the water or by increasing the pressure artificially. On the other hand, where the pressure is greatly increased, as in the boiler of a locomotive, the boiling point may even be doubled. Under a pressure of 30 pounds the boiling point rises to 120° C.; under 45 pounds, to 134°; under 60 pounds, to 144°; under 75 pounds, to 152°; under 90 pounds, to 156°; and under 150 pounds, to 180°. If the pressure upon such a body of superheated water be suddenly removed, as by a leak, the water bursts into steam, and we have an explosion comparable to that of gunpowder.

The nature of the containing vessel also influences the boiling point. Water may be made to boil several degrees higher in a glass vessel than in a metal one. Under favorable conditions, we have found this difference as great as 3° C., and other experimenters have even reported a difference of 6°. For this reason, thermometers are standardized for 100° by immersion in steam rather than in water. (See Fig. 103.)

189. **Determination of Altitude by Thermometer.**—The lowering of the boiling point of water by decrease of pressure furnishes a means of measuring height by the thermometer. At sea level the boiling point is 100° C. The decrease is not uniform, but in general it may be said that a lowering of the boiling point 1° C. indicates an ascent of 295 metres, or 538 feet for 1° F.

$$\text{Altitude} = 295\ (100 - t) \text{ metres.}$$

190. **Saturation.**—A certain volume of air, or the same empty space, can hold only a given quantity of vapor. It is then said to be saturated. It is found, however, that this quantity increases with the temperature, and that the maximum quantity is constant only for a given temperature. We may express the quantity of vapor present in the atmosphere, or in empty space, in three ways:

1. By stating in grams the absolute weight of the vapor present in, say, one cubic metre.
2. By expressing the relative saturation or humidity—that is, the actual vapor present as a percentage of the maximum vapor that might be present at that temperature.
3. By giving the vapor tension.

191. **Vapor in the Air—Dew Point.**—The most important application of these principles is found in the measurement of the water vapor present in the atmosphere, for upon this depends so many climatic and hygienic conditions. So long as the atmosphere is not saturated, and is not chilled at any one point, we are only indirectly conscious that there is any moisture present. But if a body of moist air suffers a decrease of temperature, the actual amount of water vapor remains the same, but the *relative* humidity increases, since the cool air is nearer to its point of saturation. If the cooling proceed far enough, the point of saturation is reached, and moisture thus formed is known as *dew*, if it deposit as a liquid film on solid objects; as *frost*, if it deposit as a solid film of ice; as *cloud*, or *mist*, or *fog*, if it deposit as liquid particles in the air; or, finally,

as *snow*, or *sleet*, or *hail*, if it deposit as a solid precipitate in the air. The temperature at which such precipitation of moisture takes place is called the *dew point*. In dry air, the dew point is very low, since the air must be greatly cooled before it will deposit any moisture. In damp air, on the contrary, the dew point is very high, because a slight cooling causes a precipitation of moisture.

192. **Humidity.**—A variety of instruments are used for measuring the amount of moisture in the air; among others are the wet- and dry-bulb thermometers.

Two thermometers are mounted on arms from the same stand. The bulb of one of them is covered with muslin, kept moist by a cotton wick leading from a glass of water. The constant evaporation from the muslin reduces the temperature and makes the reading of this thermometer lower than that of the free one (217). But the *rate* of evaporation depends, among other things, upon the amount of moisture already present in the atmosphere, and the fall in the wet-bulb thermometer will therefore be an indication of the hygroscopic condition of the atmosphere. The relative humidity is obtained from specially prepared tables.

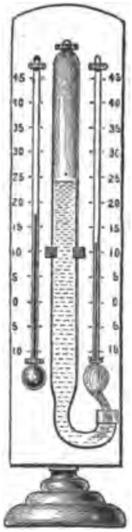

FIG. 108.—Wet- and dry-bulb thermometers.

193. **Rainfall.**—The amount of precipitation, or the rainfall, is measured in English-speaking countries in inches. The annual rainfall is the depth at which the total rain would stand had it fallen on a perfectly level surface and none been lost. It is measured by means of a rain gauge, an instrument which collects the precipitation over a given area. The water collected is poured into a tall measuring glass of small diameter, so that the rainfall can be measured to the hundredths of an inch.

There are places in the interior of the continent, in Death Valley, in the Sahara, and elsewhere, which have no rain the year round. The greatest rainfall is supposed to be in northern India, at the foot of the Himalaya Mountains, where it amounts to over 600 inches. In the English lake district the rainfall amounts to over 150 inches. It is only 24 at London and Edinburgh, yet the prevalence of fog makes these cities seem much damper than our own. In the United States it varies over a wide range. It is about 45 inches in our Eastern seaport cities. The following table shows the annual rainfall in a number of localities:

Boston, Mass.	44.96	St. Paul, Minn.	27.47
New York, N. Y	44.80	Denver, Col.	14.49
Philadelphia, Pa.	39.84	Santa Fé., New Mexico	14.25
Baltimore, Md.	43.95	Phœnix, Ariz.	7.21
Washington, D. C.	43.46	San Diego, Cal.	10.51
Charleston, S. C.	56.74	Los Angeles, Cal.	18.30
New Orleans, La.	60.52	San Francisco, Cal.	13.71
St. Louis, Mo.	41.08	Seattle, Wash.	37.44
Chicago, Ill.	34.76	Portland, Ore.	46.83

194. **Moisture and Health.**—The humidity of the air has a marked influence on comfort and health. Moisture makes the sensations of both heat and cold particularly painful. In the dry interior—in Minnesota and Dakota, for example—a temperature of −40° F. is not uncomfortable if the wind be very light, while in damper Eastern climates a temperature of 0° F. chills us through.

On the other hand, our methods of heating buildings in winter make the air too dry for health and comfort. It is not the absolute amount of moisture, but the relative amount with reference to temperature—the approximation to the dew point—that is to be considered for health and comfort. We are most comfortable when the moisture in the air is from fifty to seventy-five per cent of the amount required for complete saturation. Prof. R. De C. Ward, of Harvard University, says our houses in winter have a desert climate.

The mean annual humidity at Santa Fé is 44.8 per cent. The humidity in our houses in winter time is frequently 30 per cent, while, at the same time, the humidity outdoors may be 71 per cent.

195. **Illustrations.**—The air exhaled from the lungs, or the "breath," as we call it, is warm and moist; warm from the bodily heat and moist from the evaporation that takes place from the internal pores. If the surrounding air be cold, the moisture in the breath precipitates as a mist, and we have the phenomenon known as "seeing our breath." In summer time, the air being more moist then, a glass of cold water, or an ice pitcher, becomes covered with dew, and some people wonder how the water ever got through the glass or the pitcher, but we soon learn that the water did not come through at all. It deposited from the surrounding air. This was cooled to the dew point by contact with the cold glass or pitcher, and so had to deposit some of its moisture.

On a cool morning in spring or fall, or on a damp morning in summer, we find a fine deposit of dew on the grass, on cobwebs, stones, boards, and other objects. These cool more rapidly than the surrounding air, and so have a lower temperature; hence the deposit of dew. Again, on a damp day, a few strokes of the air pump will so far expand and cool the air in the receiver that a noticeable mist will be produced.

Tyndall mentions that on one occasion, when a ball was in progress at the Winter Palace in St. Petersburg, the rooms became overheated, and the outside doors were thrown open. The very cold air that rushed in chilled the warm, moist air to such an extent that the precipitated moisture froze and fell as snow. The same phenomenon has been known to take place in large train sheds. The hot, moist air from the locomotives, rising into the cold air in the upper regions of the sheds, produces a slight snowfall.

In Nature, the precipitation of moisture is seen on all sides. The air directly over a river or lake is moist. When this air is chilled by other air currents, the moisture precipitates, and often, in the early morning, if one is on top of a mountain, the course of a neighboring river can be distinctly traced by the serpentine line of fog. A very hot day gives rise to generous evaporation on all sides, and the afternoon of such a day is apt to see heavy thunder clouds and showers. The phenomenon of regular fog precipitation is perhaps nowhere better seen than in southern California. The air presses eastward across California, to replace the hot air of the arid regions in the southeastern part of the State and in western Arizona. This air comes off the Pacific, and is therefore moist. As it chills, the moisture falls out as a heavy fog, which may trail eastward from the coast for several miles.

The same thing is seen in the cloud banners that attach to some of the slender mountain peaks in the Alps, such as the Matterhorn. The moist air blowing against these cold, needle-like summits is sufficiently chilled to deposit its moisture. The cloud thus formed trails off from the mountain as a long, graceful banner, and takes, of course, the direction of the wind. Such a cloud may appear constant for several hours, although it is continually making and unmaking—making at the mountain, and unmaking at the end, by dissolving into the air again.

The formation of dew and frost depends largely upon the clearness of the atmosphere. (This will be explained in section 203.) On a cloudless, quiet night, the deposit will be comparatively heavy. Plants and other objects part with their heat more freely on such a night. A very thin covering, such as a piece of paper, by preventing the escape of heat, will prevent dew from collecting upon an object. Note that it is not that the paper collects the dew which would fall upon the object, but that the paper prevents the object from cooling so as to collect dew from the air which touches it. Compare this with the way an ice pitcher collects dew. On a cloudy night there is much less deposit, because the clouds act as the paper screen. If a wind is blowing, there is also less chance for deposit, since the air does not remain long enough in contact with the earth to become chilled. On cloudy, windy nights, there is rarely either dew or frost.

196. **Condensation, Solidification, and Crystallization.**— These processes are the opposite of vaporization and melting, and are always accompanied by the giving out of heat. Any change in matter which makes it more mobile, as melting, solution, vaporization, takes in heat; while any change which makes it less mobile gives out heat. (Sections 218 and 219.)

CHAPTER XX

HOW HEAT IS TRANSFERRED

197. **General Statement.**—The transference of heat means simply the transference of molecular motion from one body vibrating with a given intensity to another body vibrating with a less intensity. It is a transfer of energy in precisely the same way that mechanical reactions are transfers of mass energy. There are many ways by which mass energy may be transferred from one body to another, as we saw in studying machines. There are three ways by which heat may be transferred from one body to another—*conduction*, *convection*, and *radiation*.

198. **Conduction.**—This, although the least effective, is a very common way by which heat is diffused. If a stout iron wire have one end placed in a fire or other source of heat until it become red hot, we notice that the heat appears to travel along the wire, and, if the wire is not too long, affects the distant end perceptibly. Since the molecules are not free to move along the length of the wire, but are only free to vibrate within very narrow limits, it must be that the motion is passed along the wire from molecule to molecule, just as a blow may be passed along a line of boys, each boy receiving a blow from one neighbor and passing it on somewhat diminished (we will say) to the neighbor on the other side. We thus have at one end of our wire molecules so excited that they are red hot, and at the other end molecules that are comparatively cool. But two molecules in different states of motion can not exist

side by side without an interchange taking place, and some movement toward equilibrium. So the tendency is for the wire to become equally hot throughout its length, and for the stream of heat-motion to continue flowing from the hot to the cold end until this equilibrium is brought about.

If there were no loss of heat, the wire would in reality become red hot throughout its entire length, whatever that might be. But meanwhile the wire is in contact with the cooler air, and must give up its heat to that as well as to the colder portions of its own length. Consequently, if the wire be long enough, there will be a point where the loss and gain just equal each other. Heat will consequently flow from the source to this point, and the wire will show diminishing heat intensity. Beyond this point the wire will have the same degree of heat as the surrounding air.

We might define conduction, then, as a transference of heat from molecule to molecule, and limited mainly to solid bodies. There is slight conduction among the molecules of fluids, but the mobility of the molecules makes it possible for them to be the direct carriers of heat without passing it along molecule to molecule, as in the case of the more rigid solids.

Solids and fluids differ much in their conducting power. In general, the more compact the structure, the greater the conductivity. Hence the metals are the best conductors; wood and stone are poor conductors, and fibrous materials, such as fur, felt, and cloth, which contain many air spaces, are bad conductors. The best conductor we have is silver; the worst conductor, air. The following table arranges the metals in order of diminishing conductivity relative to silver:

Silver	1.000	Iron	.119
Copper	.736	Steel	.116
Gold	.532	Lead	.085
Brass	.231	Platinum	.084
Zinc	.190	Bismuth	.018

There are many practical ways of showing the different conducting power of the metals. Thus wires of different metals are fastened into the side of a water-tight box, as shown in Fig. 109, and are coated with wax along the projecting ends. When boiling water is poured into the box, the unequal melting of the wax shows the unequal conductivity of the metals.

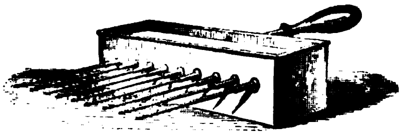

FIG. 109.—Conduction.

Liquids are very poor conductors. A test tube full of water may be made to boil in the upper portions, while the lower portions are quite cool.

199. **Applications.**—There are hundreds of daily applications of these principles. The non-conductors are used either to keep heat out or to keep it in. In the former case, as in ice-houses, the walls are made of brick, straw, sawdust, ashes, etc., and serve to keep out heat. But more frequently non-conductors are used to keep the heat in. In buildings, both of brick and of wood, a hollow air chamber is allowed between the outer and the inner walls, since, as we have seen, air is the poorest conductor. For the same reason, double windows keep out the cold, not so much by guarding us from currents of air as by interposing an air chamber. The same principles obtain in our clothing. Loose, fibrous materials and loose garments are warmer than close, tight-fitting goods. Flannel blankets are warmer when new, and before the fibers have been closely matted together. The Norwegian cooking box is another application. It is made of wood and lined with felt. A covered metal pail, containing water and the joint of meat boiling hot, is placed inside the cooking box, and the whole carefully closed. The loss of heat is very slow, and the cooking process goes on for several hours without the application of any additional outside heat.

The furnace in the basement for heating houses is merely a large iron stove, around which a wall of brick is built to prevent the heat from passing out into the cellar. If it is a "hot-air" furnace or a "hot-water heater," its heat is carried to all parts of the building by a process to be discussed in the next section. If it is a "steam-heater," its heat is stored, distributed about the building, and recovered by processes to be discussed in sections 213 and 218. The ducts which carry the hot air, hot water, or steam about the building are incased in brick walls, where that is possible, to prevent the loss of their heat in transmission. Where these ducts pass through the open basement, they are sometimes covered with non-conducting material of loosely woven hair or felt. Wrapped with this covering, steam pipes are frequently carried long distances underground to heat remote buildings. In comparison with other materials, the earth is not a very bad conductor, and yet conduction is such a poor method of diffusing heat that, as has already been said, although heat so intense exists beneath the surface as to fuse the rocks, yet that heat does not penetrate to the surface sufficiently to effect a rise in temperature of one thirty-sixth of a degree.

Water pipes are laid a few feet underground to prevent them from freezing in winter—that is, the earth is a sufficiently poor conductor to prevent the heat from passing out of the water to such an extent that it may freeze. (It is better to state it thus, than to speak of cold passing in through the earth to the pipes; just as we speak of light coming into a room through a window, but do not speak of darkness doing the same.) We should remind ourselves that all things have some heat, and that when things grow cold they are simply losing some of their heat.

We sometimes ride in an open carriage in the coldest weather and are quite comfortable, because we wrap ourselves in what we call warm clothing and blankets. We sleep in cold rooms comfortably, or may be even too hot, under our "warm" blankets. Now, they are not warm at all—indeed they are just the temperature of all other things around them, so that if we wrap a thermometer up in "warm" clothes or blankets it will not show the least bit of rise in temperature. In order that our ideas may be clear we should use some other word than *warm* to describe these coverings. What we need is some word like non-conducting, which would imply that they keep the heat of our bodies from passing off. Our bodies generate at all times a great deal more heat than we need. It is only necessary that we regulate the outflow of this heat so that the temperature of our vital organs may be always about 98° F., night and day, summer and winter, at work or at rest.

The chemical action, which, as was said in section 160, produces heat in piles of green grass, new hay, piles of oily cotton waste, etc., is very slow and produces very little heat per hour, but these substances are such poor conductors that the heat is not allowed to pass off, and it is possible for it to accumulate until it reaches the kindling temperature of the substance, when "spontaneous" combustion will take place.

Snow protects vegetation in winter from killing frosts. It must be remembered that solutions do not freeze as readily as pure water, and therefore the juices of plants will not freeze at 32° F. While the snow can not enable the plants to rise above that temperature, it does prevent them from falling much below it; among other reasons, because being filled with air spaces it is a very poor conductor.

200. **Convection.**—This practically means the transfer of heat by the transfer of the heated body itself. Fluids are heated almost entirely by this process. If we consider the heating of water in a teakettle, or, better still, in a glass beaker, where we can see what is going on, we shall notice that the whole fluid is in a state of constant motion. A

little sawdust in the water will make the action plainer. The source of heat is under the beaker (Fig. 110), and the bottom is naturally the hottest part. The water directly in contact with this becomes heated, expands, and in so doing grows lighter. The colder, heavier water, therefore, presses down under this and buoys it up toward the surface. As soon as this becomes cooled and the other hot, another overturning occurs, and so the process goes on until the whole mass of water is heated to the boiling point, if the source of heat be intense enough, or to the point where loss and gain of heat just balance. In the same way a stove or a steam radiator warms the air of a room. The air is such a poor conductor that we should be badly off if we had to depend upon its passing along the heat to us by conduction. In reality, the air in contact with the stove or radiator becomes heated and is buoyed up by colder, heavier air.

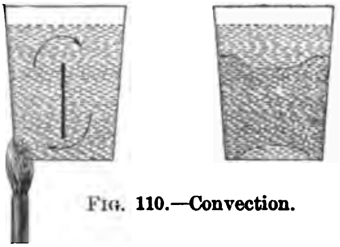

FIG. 110.—Convection.

This is illustrated by Fig. 111. We may think of the air in the pasteboard box as a pair of scales with columns of air of equal weight standing upon either scale pan. A candle is lighted at the bottom of column *a*, which expands it and drives a portion of the air out. What remains is no longer heavy enough to balance the weight of the column *b*, and it pushes down and

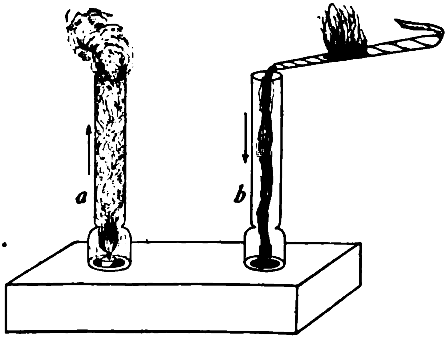

FIG. 111.—Convection.

forces a movement of air through the box and up *a*, which continues as long as the heat is supplied by the candle.

The upper part of a room is warmest and may be many degrees above the air near the floor. We notice it very plainly if we have occasion to climb up on a stepladder to hang a picture. If we set the door of a room ajar, we may, by means of a candle flame, show that currents of air (cold air) are coming in at the bottom and currents of air (warm air) are going out at the top of the door.

If a room is to be ventilated by the windows, the best way is to make a small opening at both top and bottom, since this promotes convection currents.

This principle of convection is of the utmost importance in Nature. It is the great source of movement in the atmosphere. The unequal heating of the air above land and sea creates our so-called land and sea breezes. The greater heat at the tropics causes the air there to expand, and in consequence the colder air from polar latitudes pushes in and takes its place. This action, combined with the earth's daily rotation, is the source of those permanent air movements known as the trade winds.

The heating of water by convection, and the resulting convection currents in oceans and lakes, are great equalizers of temperature the world over. By convection we heat the water in the kitchen boiler from the stove. By a similar process houses are heated by hot water. The hot-air furnace is dependent upon convection to convey its heat over the house; and many methods of ventilation depend upon this way of promoting air currents.

201. **Radiation.**—This third process of transferring heat is different from either conduction or convection. It is so closely allied to the propagation of light that we shall consider it at length when we come to take up the mechanics of the ether. We shall discuss it here rather briefly.

Consider how we get heat from a fire on the hearth. Evidently it is not brought to us by conduction, for air is almost an absolute non-conductor. Neither can it reach us by convection, for all the air currents move from us toward the fireplace, and up the chimney. Indeed, it is found that the heat would reach us quite as well, and even better, if there were no air or any other substance between us and the fire. The sun, and every other heated body, appears to give off heat in all directions throughout space. Yet we believe that heat, being molecular motion, can not exist apart from matter, and consequently we think it can not be transmitted as *heat* through space. Space reacts as if it were filled with some medium, neither gaseous nor liquid, but having some properties of a solid. The more we study the phenomena of space, the more we seem compelled to assume that all space is filled with a very tenuous medium called the ether, which is capable of transmitting a variety of wave motions, some of which beget heat, some light, and some electrical phenomena, upon reaching the earth. Hot bodies are supposed to be able, by means of molecular motions, to set up vibrations in the ether, and the ether is capable of setting up molecular motions in bodies of matter. Heat transferred by radiation is supposed, therefore, to be transferred by a wave motion of the ether. It is called radiant heat, because it goes out in all directions through space in straight lines or radii, which have their center in the heated body. This wave motion has a velocity of about 186,000 miles per second, and for such distances as we have to deal with on the earth, may be considered instantaneous.

All matter with which we are acquainted radiates ether waves, because all substances have some heat—that is, molecular motion; so that every portion of matter is radiating heat to every other portion of matter. The hotter ones radiate more abundantly than the cooler ones, and thus tend to bring about a state of equilibrium. Moisture in the air converts ether waves into heat. If we go up into the upper regions of our atmosphere, either upon a mountain top or in a balloon, where there is scarcely any moisture, we find that the sun's rays produce intense heat in us, but the air about us is, nevertheless, extremely cold. Tyndall says: "A joint of meat might be roasted before a fire with the air around the joint as cold as ice. The air on high mountains may be intensely cold, while a burning sun is overhead; the solar rays which, striking on the human skin, are almost intolerable, are incompetent to heat the air sensibly, and we have only to withdraw into perfect shade to feel the chill of the atmosphere. I never, on any occasion, suffered so much from solar heat as in descending from the 'Corridor' to the Grand Plateau of Mont Blanc, on August 13, 1857. Though Mr. Hirst and myself were at the time hip-deep in snow, the sun blazed against us with unendurable power. Immersion in the shadows of the Dome du Goute at once changed our feelings, for here the air was at freezing temperature. It is not, however, sensibly colder than the air through which the sunbeams passed; and we suffered, not from the contact of hot air, but from radiant heat, which had reached us through an icy cold medium."

A hot body, by its molecular motion, sets up ether waves. These ether waves may be sent through a lens cut out of ice and focused upon paper, there to set up those molecular motions which we call heat and set fire to the paper. It was heat in the radiating body, and it became heat again in the body or bodies which received it, but it was not heat in passing.

202. **Absorption, Radiation, and Reflection.**—When ether waves impinge upon matter, one or more of three things must happen: 1. They may be transmitted without producing any effect upon the substance. This not only happens with dry air, but it may also happen with certain liquids, and even solids. 2. They may be reflected wholly or in part. 3. They may set up molecular motions (heat) in the substance, wholly or in part. This is called absorp-

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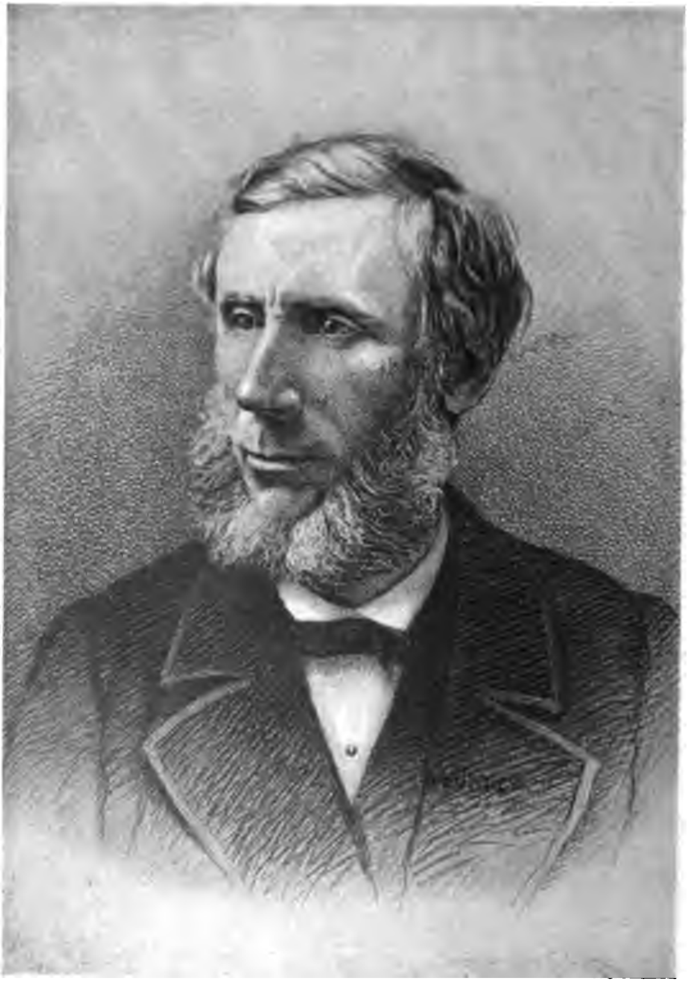

JOHN TYNDALL (1820-1893).

Succeeded Faraday as professor in the Royal Institution of Great Britain. No man has done more than he to disseminate science by his lectures and writings.

tion. The law of the conservation of energy obtains here. Suppose we put a glass screen between us and the fire, and that ninety per cent of the radiant energy which falls upon the glass is converted into heat, then the remaining ten per cent must be accounted for as transmitted or reflected. It must also be remembered that all of the ninety per cent which was converted into heat will, by molecular motions in the body, set up again an exactly equivalent amount of ether vibration and then radiate off again. The power to arrest ether waves and convert them into heat varies much with different substances. A piece of zinc will protect woodwork from the heat of a stove better than a sheet of asbestos can do it, because the zinc reflects back most of the ether waves which strike it, while the asbestos converts a very large portion of them into heat and will scorch the paint or the wood underneath it. Indeed, the thinnest coating of metal, like gilt lettering, will protect wood from the heat of the stove, while ordinary paint, no matter what color, so far from protecting it, converts the ether waves into heat and scorches the wood. For this reason water in a clean metal dish before the fire will not heat as rapidly as water in a metal dish that has been smoked or coated with varnish, enamel, etc. In the first case the waves which come to the dish are reflected, and in the second case they are converted into heat and raise the temperature of the water. If hot water is poured into these two kinds of vessels, its heat will radiate out from the coated metal vessel faster than from the other, and a thermometer will show a more rapid loss of temperature. In general, those forms of matter whose molecules are most readily set in motion by the ether waves (good absorbers) are best capable of setting up ether waves by their molecular motions (good radiators).

203. **Relation of Heat and Light.**—When we watch an iron ball slowly heated until it gives out light—first a dull red and afterward a bright light—we very naturally are led

to suspect that heat and light are closely akin to one another. This we shall find to be true when we study light, and we shall then learn in what their kinship consists. It is sufficient at present to say that it is analogous to the relation which exists between sounds of low pitch and those of high pitch. The sun sends us both kinds of ether waves—those which give us the sensation of light and those which give us the sensation of heat. One is readily converted into the other. Dry air is perfectly transparent to both kinds of rays, but the moisture of our atmosphere absorbs most of the heat-producing rays. The moisture radiates this heat in all directions, and thus a large portion of it passes off into space again without ever reaching the earth. Waves which give us the sensation of light pass, without much loss, through the air to the earth, where they are partly reflected again into space, but for the most part are absorbed and converted into *heat*. This heat sets up ether waves of the heat-producing kind which would pass off into space if the moisture of the air did not arrest them, absorb them, and radiate a portion of them back again. Thus it will be seen that the moisture of our atmosphere acts as a sort of valve to entrap sunlight and warm the earth. What the moisture of the air is to the earth, the glass is to the "hot bed" in the garden, or the glass roof to the greenhouse. Indeed, the same thing is true in a measure of a shingle roof, or any kind of cover, as for example an umbrella; for, however opaque these coverings may appear to the eye to be, they are in reality transparent to a large number of the rays which come from the sun and produce heat in objects upon the earth; but these same coverings are opaque to the rays which these warm objects upon the earth send out, and they prevent them from passing off again into space. A covering of snow protects the crops in the same manner that a "hot bed" protects young plants; although it can not raise the temperature above 32° F., it does prevent it from falling below that degree, and there are many plants to which this temperature is not injurious.

Because different substances differ in their power of radiating, no two things are likely to be of the same temperature. This is why dew and frost collect more upon some things than upon others, and they thus tell us which things are the best radiators. It should be noted that dew and frost collect more upon the grass than upon the bare ground. Which of these spots is, therefore, the best absorber of the sun's rays? From which will a thin layer of snow disappear sooner? Why does earth sprinkled upon snow melt away the snow from underneath it?

In Sahara the cold at night and the heat by day are equally painful to bear. Whenever the climate is dry the daily range of temperature is great. This is the marked difference between mountainous or interior climate, and that by the sea or other bodies of water.

A piece of paper will prevent the loss of heat from a plant during the night, so that a thermometer may stand 10° higher under the paper than outside.

The clouds act like this paper screen, and hence we have more dew or frost at night when the sky is clear than when it is overcast. Indeed, a thermometer will rise and fall at night as a cloud is passing over.

A thermometer resting on the grass at night has been found to be 14° lower than one suspended four feet above it.

Painted metals will collect more dew than bright metals. This is merely a question of temperature, as the thermometer will show.

204. **Radiometer.**—This consists of a glass globe from which nearly all the air has been removed. A light vane, made of tiny mica plates mounted on an aluminium frame, is so arranged that it is free to rotate on the steel pivot in the center of the globe. One face of each mica plate is darkened with lampblack. When the radiometer is exposed to radiant energy coming from the sun, or from a cup of

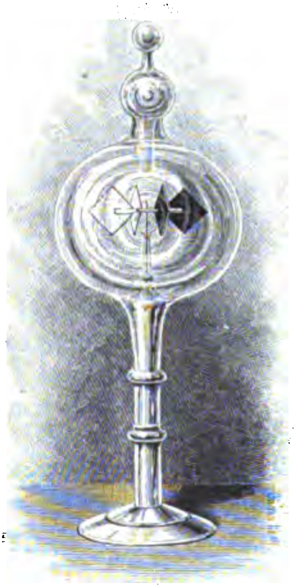

FIG. 112.—Radiometer.

hot water, or the warm hands of a person, the little vane begins to rotate, spinning the more rapidly as the radiation is greater. The darkened faces absorb more heat, and the straggling air particles coming in contact with these faces are themselves heated and fly off. The reaction sends the vane in the opposite direction, and so it spins on its pivot, the darkened face in the rear. If a tin cup be smoked on one side, filled with hot water and held near the radiometer, we may show, by turning the cup about, that the blackened side radiates more heat than the bright metal side. We may now cover the bright metal side with white paint and show that it radiates as well as lampblack. The power to absorb is always equal to the power to radiate, and the white paint absorbs *heat-radiation* as readily as lampblack does, but this is not true for *light-radiation*, of which, as we know, the white reflects more.

CHAPTER XXI

CALORIMETRY AND SPECIFIC HEAT

205. **Measurement of Heat.**—Heat, like all forms of energy, is a measurable quantity. The process of measuring heat is one of great scientific and practical importance. We may measure either of the two aspects of heat that we have mentioned, either its degree or its amount. We call the first measure *Temperature*, and the second *Quantity*.

206. **Temperature.**—This, as we have seen, corresponds in mass-mechanics to velocity or rate of motion, and is quite independent of the amount of matter in motion. In heat-mechanics temperature is the degree of molecular motion, and is also quite independent of mass.

As temperature can not be directly measured in C.-G.-S. units, we are forced to devise some conventional and quite empirical unit, and to make our measurement consist merely of a statement of relative intensity. This we do with a thermometer (167).

207. **Quantity of Heat,** as we have seen, corresponds in mass-mechanics to momentum. It is not only the degree of heat, the temperature, but it is also the amount of matter heated. It is evident that although a cup of boiling water is hotter than a ten-gallon tank of lukewarm water, the tank has a greater *quantity* of heat and will do more toward warming a cold room. So it is evident that a great lake at a temperature of 40° F., although it is not hotter, yet it contains more heat than a cup of boiling water, and will do more to modify the winter climate of that region

than many thousand cups of boiling water could. The relation of temperature to *quantity* of heat is analogous to the relation of water pressure to volume of water. The mountain stream may exhibit high pressure of water; the quantity may, however, be too small to be useful. We can not measure quantity of heat in C.-G.-S. units, and so must devise an empirical unit. The *Calorie* is our name for such a unit. It is the quantity of heat needed to raise the temperature of 1 gram of pure water 1° C. It is a mere convention. We might use 1 kilogram, or 1 pound, or 1° F., and often do, but this unit is, on the whole, the most convenient.

208. **Specific Heat.**—As soon as we come to measure temperature and quantity of heat, we come upon a very characteristic and important difference in the behavior of bodies toward heat. If we take a kilogram of water and a kilogram of some metal such as lead or mercury, and raise the temperature of water and metal the same number of degrees, we find that it takes a different and much larger amount of heat to increase the temperature of the water than that of the metal. We express this by saying that different bodies have different capacity for heat. As water absorbs a great amount of heat in changing its temperature by a given number of degrees, we say that water has a great capacity for heat. We measure the heat capacity of any body by comparing it with the capacity of water. We call the ratio *Specific Heat*, which we may define as the heat capacity of a given mass of a substance compared with the heat capacity of the same mass of water.

209. **Determination of Specific Heat.**—There are several methods in use for the determination of specific heat.

The method of mixtures is the one generally used, and is the only one suitable for elementary work. In this method we heat a known mass of the body to a definite temperature, say 100° C., and then plunge it into a known mass of water whose temperature is also known. The temperature of the water is generally taken at that of the room, and consequently rises when brought into contact with the hotter body. The water is well stirred, and when the temperature ceases to rise, the hot body and the water must have reached the same temperature. The increase in the temperature of the water multiplied by its weight in grams gives the quantity of heat imparted to the water by the cooling body. The heat gained by the water and the heat lost by the body are manifestly equal. The total number of heat units given out by the cooling body, divided by the number of degrees of fall in temperature, gives the amount of heat for each degree, and this amount divided by the number of grams of weight in the body gives the amount of heat yielded by each gram as it falls one degree. Since the temperature of the vessel containing the water, as well as that of the water itself was raised, its heat capacity must also be taken into account.

The case will be made clear by an example. Suppose we take 100 grams of water in a copper cup weighing 12 grams, both at the temperature of the room, which is 17.5° degrees. From a vessel of boiling water we lift a piece of lead weighing 100 grams and put it into the copper cup of water. We stir the lead about, so that it and the water may become of the same temperature, and when the temperature becomes stationary we find it is 20°. The lead has given out heat enough to raise

100 grams of water 2.5 degrees = 250 heat units, and
12 grams of copper 2.5 degrees $= 12 \times 2.5 \times .0933$* $= 2.8$ heat units.
Total number of heat units given out by the lead = 252.8 in falling 80 degrees.

Amount given out for each degree $\frac{252.8}{80} = 3.16$ heat units.

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* See table on the following page for specific heat of copper.

Amount given out by each gram for each degree of fall in temperature $= \frac{3.16}{100} = .0316$. If one gram of lead gives out .0316 heat units in falling one degree, it would require .0316 heat units to raise one gram of lead one degree. This is called the specific heat of lead. In accurate work, allowance must also be made for the heat capacity of the thermometer, and for the loss of heat by radiation; but we neglect these, and still get fair results.

TABLE OF SPECIFIC HEATS.

Water	1.000
Aluminium	.212
Iron	.114
Copper	.093
Tin	.056
Silver	.057
Mercury	.033
Gold	.032
Platinum	.032
Lead	.032
Glass	.019
Sulphur	.203
Graphite	.218
Charcoal	.241
Ice	.504
Alcohol	.610

210. **Applications.**—Among liquids, water has the largest specific heat, and this is of immense importance in the economy of Nature. Water acts everywhere as an equalizer of temperature. It has such great capacity for heat that it warms up slowly and cools down slowly. Hence the climate near large bodies of water is much less subject to extremes of temperature than places surrounded by land. The movement of large bodies of hot water from the tropics to the poles, and of cold water from the poles to the tropics, make habitable large areas of land that would otherwise be lost to human uses. The Gulf current greatly moderates the climate of the British Islands and of the northwest coast of Europe, while the Japan current performs the same service for the northwest coast of America.

The kitchen range may be much hotter than the water in the hot-water tank which is connected with it, but if the fire goes out on a cold winter night the warm water in the tank will give out its heat all night long and perceptibly warm the room, while the stove will have parted with its comparatively small amount of heat in a very short time.

The summer sun beats alike upon the seashore and the adjacent waters of the sea, but the specific heat of sand being much less than that of water, its temperature rises much higher than the water. The air over the water will, therefore, be cooler than that over the land, and will press toward the land, giving a "sea breeze." At night the land, like the kitchen range, will lose its heat sooner than the water does, and the air over the land will become cooler than that over the sea, and will press toward the sea, giving a "land breeze."

CHAPTER XXII

LATENT HEAT

A. HEAT DISAPPEARS WHEN SOLIDS LIQUEFY

211. **Heat latent in Solutions.**—If we apply heat to some fragments of ice, the temperature rises until the whole stands 0° C. The ice then begins to melt, but though the application of heat be continued, no rise of temperature takes place until all the ice has melted and passes into water at 0°. The heat applied during this interval has accomplished no change in the temperature, but has been solely spent in changing the ice at zero into water at zero. Evidently a large quantity of heat has disappeared in the process. We say that it has become *latent*. It has been employed to do internal work among the molecules, and is in the form of potential energy. All this heat may be recovered again, as we shall see in section 219.

Common salt put into water will cause its temperature to fall several degrees. It abstracts heat from the water, as it dissolves or passes into the liquid state. This heat does not raise the temperature of the salt, but becomes latent. This is true of all solids when they dissolve.

Each solid has its own peculiar power of rendering heat latent. Ice, for example, absorbs 80 heat units for each gram liquefied. And it is a physical impossibility for ice or snow—any form of water in the solid state—to pass into the liquid state without its absorbing this amount of heat; but ice and snow do not take heat very readily by either conduction or radiation, and this explains why they linger so long even under a hot sun. Every one must have sometimes wondered that a cake of ice will endure for so long a time the broiling summer's sun, and that snow will sometimes last until late in spring.

212. **Freezing Mixtures.**—When we want only a moderate cold, as in the case of drinking water, the ice is simply dissolved in water. When the ice melts, we have, of course, water at 0° C. as the immediate result, but we also have the original drinking water greatly cooled, since the ice, to melt, must take its heat of liquefaction, 80 calories per gram, from the surrounding water. So it is possible, by using little water and much ice, to keep the contents of a water pitcher at 0° C. for a considerable time, since the ice can melt only as it can absorb the requisite heat from the surrounding water.

When a greater cold is wanted, as in freezing creams and fruits and ices, it is gained by mixing salt with the cracked ice. The action is double—the melting of the ice and the solution of the salt—and both processes require heat; that is, are cold-producing. The salt (sodium chloride, $NaCl$) has a great affinity for water. We express this by saying that it is deliquescent. We all know how damp table salt becomes if exposed to the air on a moist day. So strong is this affinity that the salt melts the ice in order to dissolve in the water formed. But, in order to dissolve, the salt must itself absorb its own heat of liquefaction, and so contribute its share to the production of cold. It is possible in this way to obtain a temperature as low as $-22°$ C.

The act of solution is always accompanied by a lowering of the temperature. If we take a mixture of solid ammonium chloride (NH_4Cl) and ammonium nitrate (NH_4NO_3) and place them in a beaker, and then add just enough cold water to dissolve them, we shall have a temperature considerably below zero. This can be shown by stirring the mixture with a chemical thermometer and noting the reading, or, better still, by using a small test-tube with a little water in the bottom, as a stirrer. The water will be frozen solid, and may be turned out on the table as a transparent lump.

The faculty of salt to liquefy ice is made use of to remove ice from the pavements in cold winter weather. It liquefies the ice, although it makes it colder than it was before. We should, therefore, avoid saying it *melts* the ice. The salt solution which is formed flows off and clears the pavement. It does not freeze until a very low temperature is reached.

B. HEAT DISAPPEARS WHEN LIQUIDS VAPORIZE

213. **Heat latent in Vapors.**—When we supply heat to water its temperature rises constantly until it reaches 100° C., and here a halt takes place until all the water at 100° has been converted into steam at 100°. The heat meanwhile has been spent in changing the water into water vapor. Evidently a large quantity of heat has disappeared in the process, and yet all this heat may be recovered again, as we shall learn in section 218. We therefore say that it has become latent. When water or any other liquid changes its state, passing from liquid to gas, heat is apparently used up in producing this change of state. Each liquid has its own peculiar power of rendering heat latent. Water, for example, absorbs 537 heat units for each gram vaporized. It is not possible for water or any other liquid at any temperature to pass into the vapor state unless it is supplied with the number of heat units required to bring about that change. That is, 1,000 grams of water (about 1 quart) must absorb 537,000 heat units before it can vaporize. This shows why a little shower on a summer day, whose water quickly evaporates, cools the earth so much.

Those who have seen experiments with liquid air must have marveled that the liquid does not fly away into the gaseous state more readily than it does. This is because it is unable to appropriate to itself the necessary amount of heat to change its state.

In general, we may say that when substances pass to a *more* fluid state—solids to liquids, liquids to gases, gases in expanding—heat is absorbed, and that when substances pass to a *less* fluid state—gases in condensing, gases to liquids, liquids to solids—heat is given out. For the same substance, the amount of heat absorbed in any given change is precisely the same as the amount given out when the change is in the opposite direction.

214. **Absolute Temperature.**—We have called attention to the fact that temperature is analogous to velocity in mass-mechanics. But velocity may diminish until it finally ceases altogether, and the body comes to rest. If the analogy were complete, there would be a corresponding point in the thermal scale where molecular activity would cease, and the body be devoid of all heat. Such a condition would be *absolute cold*, or the *absolute zero* of temperature. It has never been attained experimentally, but we can estimate it.

If a body of air at 0° C. be chilled to $-1°$, or heated to $+1°$, its volume will change by $\frac{1}{273}$ of its original volume at 0°. If, therefore, we should heat it to $+273°$, its volume would increase by $\frac{273}{273}$ of its original volume. That is, its volume would just double. If, now, we should cool this body of air to $-273°$, it ought to shrink $\frac{273}{273}$ of its original volume, and therefore cease to have any volume whatever. Before reaching that temperature, however, every gas would become liquid, and cease to follow Boyle's law. This point, $-273°$ C., we call the absolute zero.

We may construct a scale of absolute temperature by referring all readings to the absolute zero. We can readily do this in the centigrade scale by simply adding 273° to all ordinary readings. Thus all readings in absolute temperature must be positive. Water freezes at 273° and boils at 373°.

215. **The Production of Cold.**—Cold is the absence of heat, and is simply relative. It means a lower degree of molecular energy. Cold is produced, therefore, by the reversal of all those processes which are the sources of heat. However, it is not practically possible to reverse all of them, such as solar radiation, mechanical motion, and electricity. Nor can we, except in rare cases, make chemical reaction a source of cold. The reverse of chemical combination—that is, chemical decomposition—requires the taking in of heat, but the process is not self-promoted and can not, therefore, be used as a source of cold. Practically we are thrown back upon three sources for the production of all artificial cold—expansion of gases, evaporation of liquids, and the dissolving of solids.

216. **Expansion of Gases.**—This is a very effective source of *cold*, but it is rarely used in the arts, because there are more convenient methods. It usually appears, indeed, as an inconvenience. Motors driven by compressed air become very cold, and consequently brittle, by the expansion of the air in the cylinder. It is sometimes the custom to surround parts with running water in order to equalize temperatures. The cold produced by expanding air may be beautifully seen in the receiver of an air pump. On a damp day a few strokes of the pump suffice to fill the receiver with fog, a precipitation of moisture due entirely to the chilling effect of expansion.

In Nature, the expansion of air in the upper regions of the atmosphere is a source of considerable cold, and is probably one reason why the higher clouds are made up of tiny ice crystals instead of globules of condensed water vapor. Whatever be the cause of this fall in temperature, it amounts to about 1° F. for each 332 feet of elevation.

217. **Cold by Evaporation.**—This is the great source of artificial cold, and also one of the most convenient in way

of application. It has already been incidentally referred to (192).

Whenever a liquid evaporates, it must take in its own heat of evaporation, and so make surrounding objects cold. In ordinary evaporation, the heat is supplied from somewhat wide territory as rapidly as it is needed, but by increasing the rate of evaporation and shutting out external sources of heat, we may produce very intense artificial cold.

Remembering the five factors upon which evaporation depends, it will readily be seen that we can not well use the first, temperature, since that would be fatal to our purpose, but we can use the other four conditions. We can increase the surface, we can diminish the pressure, we can remove the vapor as fast as it is formed by pumping or by constantly renewing the atmosphere.

The porous water jars of the East depend for their cooling action upon the large surface exposed, and the renewal of atmosphere which comes when the jars are hung in a good draught of air. They are made of unglazed earthenware, and consequently the water makes its way through the pores to the surface, and by evaporation cools the water still in the jar several degrees below that of the surrounding air. The experiment may be made by using the porous cup of a battery, and either placing it in a good draught of air, or directing a jet of air against it from a bellows or pump.

The Carré Ice Machine, one of the oldest, depends on the evaporation of liquefied ammonia gas, NH_3. Under ordinary conditions NH_3 is a gas, but under a pressure of seven atmospheres it becomes a colorless liquid which boils at −33.7 C. The liquefied gas is passed through coils surrounding the body of water to be frozen. By simply removing the pressure the NH_3 passes back to the gaseous state, and in doing so absorbs enough heat to reduce the temperature of surrounding objects to something below zero F.

The ammonia gas may be again liquefied, and so used over and over again with little loss. The ice is thus made at the cost of the mechanical energy used in liquefying the ammonia.

The most intense cold is produced by the evaporation of much more difficultly liquefiable gases, such as carbon dioxide, CO_2, and even the elementary gases N and O. By the evaporation of N, a cold of − 225 C. has been attained.

The value of bathing the forehead with cologne or bay rum, in case of headache or fever, comes from the cooling effected by the evaporation of the alcohol.

A simple application of evaporation, in freezing water, is an ice machine, consisting merely of an air pump provided with a chamber containing strong sulphuric acid, H_2SO_4. A flask, half filled with water, is connected by means of a rubber stopper and tube with the acid chamber and the pump. A few strokes of the pump remove most of the air from the flask, and under the reduced pressure the water begins to evaporate very rapidly. But the H_2SO_4 has strong affinity for water vapor, and absorbs it so rapidly that it re-enforces the air pump in maintaining a vacuum, and so hastening the evaporation of the water in the flask. Under this greatly diminished pressure, bubbles of vapor form throughout the mass of the liquid, so that it boils at a very low temperature. But, meanwhile, the rapid evaporation of the water has been carrying off so much heat that a film of ice begins to form on the surface, while the water below continues to boil. We have thus the spectacle of water boiling and freezing in the same vessel and at the same temperature. When the flask is brought on the table, those not in the secret naturally wonder how such a large sheet of ice got into such a small-necked bottle.

This experiment may be made with the ordinary air pump by introducing into the receiver a vessel containing strong H_2SO_4 and another containing water. It was in this form that the experiment was originally made by Leslie.

Wollaston's Cryophorus (Fig. 113) illustrates the same principle. It consists of a U-tube with a bulb at each end. One bulb is half filled with water, and the other bulb and the tube itself with vapor of water. When this second bulb is surrounded by cracked ice, the water condenses, and thus reduces the pressure inside the tube. The water in the other bulb rapidly evaporates, and crystals of ice are seen to form on the surface.

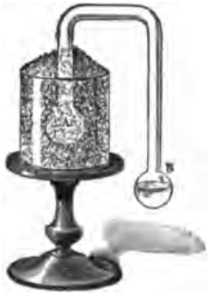
FIG. 113.—Wollaston's Cryophorus.

If two large watch crystals be moistened on their convex sides and placed on top of each other, with some highly volatile liquid, such as ether, placed in the upper crystal, it will be easily possible to freeze the two crystals together by the rapid evaporation of the ether. This may be brought about by simply blowing on its surface, or by directing an air jet against it from a bellows.

Still another instance. The cold produced by evaporation may be readily observed by dipping the bulb of a chemical thermometer into ether or chloroform, or even into alcohol or water, and rapidly swinging it in the air; or by wetting a cloth with one of these liquids, wrapping the cloth around the bulb, and then swinging the thermometer as before, or directing a blast of air against the cloth.

Besides these applications, there are numerous other circumstances where we wish an intense cold. In engineering work it is now the custom to freeze "quicksands" by means of liquefied ammonia gas, NH_3. A tunnel or shaft can be driven through this solid mass of sand and water, when it would be quite impossible to deal with the semi-fluid, shifting quicksand.

A freezing cold is also used in microscopic work in studying delicate organic structure that must be cut into sections thin enough to allow the light to pass through. It is so used in the Department of Agriculture at Washington in investigating diseases of domestic animals. The heart, liver, or kidney, or whatever organ is under examination, is first frozen stiff, and then, by means of a sharp razor, a wonderfully thin section is sliced off and mounted between little glass slides before it has a chance to melt and become unmanageable.

All volatile liquids, such as alcohol, ether, benzine, etc., feel cold to us. Yet the liquids are not cold, except when they are allowed to evaporate.

The water bath in the laboratory and the double boiler in the kitchen are used because the evaporation of the water will absorb all heat above a certain temperature, and prevent the "burning" of the food, etc. Upon a mountain top, where the pressure of the air is reduced, evaporation proceeds more rapidly, and it may abstract heat to such an extent as to prevent the cooking, by boiling water, of certain things which require a temperature of at least 100° C.

All animals produce more heat than they need. Their life processes depend upon the elimination of superfluous heat. This is absorbed chiefly by the evaporation of moisture produced from countless pores in the skin. Cold contracts the surface blood vessels and sends the blood to the interior of the body where it will not lose so much heat, but it also contracts the mouth of these pores—as evidenced by the so-called "goose pimples"—checks the flow of perspiration, and thus evaporation and the consequent loss of heat are reduced. Heat causes the surface blood vessels to relax and the warm blood to flush the skin where it cools. Heat also opens the pores, causes the perspiration to flow, and if the conditions of evaporation are favorable, we do not suffer with the heat. If, however, there is great humidity in the atmosphere, so that evaporation does not proceed readily from our bodies, we suffer greatly from the heat, and we call it a "muggy" day.

C. HEAT REAPPEARS WHEN VAPORS LIQUEFY

218. **Heat recovered from Vapors.**—When any gas passes to the state of a liquid, its latent heat is given out. If the gas be steam, then the liquid must be water, and each gram of condensed water at 100 represents the liberation of 537 calories. This method of heat production is illustrated in our steam radiators. The condensing steam yields its heat to the iron radiator, and this in turn to the apartment. In Nature, the liquefaction of vapor is a most important source of heat. Whenever the moisture in the atmosphere condenses into rain or snow, heat is liberated. Consequently, precipitation is always accompanied by rise of temperature. We notice a moderation of the weather during a rain. It has been calculated that the moist air accompanying the Gulf Stream yields as much heat to Great Britain, by the precipitation of the moisture, as is brought by the Gulf Stream itself.

D. HEAT REAPPEARS WHEN LIQUIDS SOLIDIFY

219. **Heat recovered from Solutions.**—The freezing of water requires the giving up of the exact amount of heat required to liquefy the ice, 80 calories for each gram, and is a most important natural source of heat. Farmers understand this, and put tubs of water in their vegetable cellars on a cold night, so that if the temperature falls below 32° F. the freezing of the water will give out such quantities of heat as shall prevent the temperature from falling far below 32°, and the vegetables will not freeze until a temperature considerably below 32° is reached. Ponds and lakes, by the freezing of their waters, do much toward preventing the temperature of the immediate neighborhood from falling far below 32° F. For the same reason the atmosphere is genial and agreeable during a quiet snowstorm.

220. **Recapitulation.**—Suppose 1,000 grams of ice at −10° C. rises to 0°. The specific heat of ice being .5 (209), this

would require the absorption of 5,000 heat units. Next let us suppose this ice to melt. This would require 80 × 1,000 = 80,000 heat units. If now we heat this quart of water to the boiling point, 100 × 1,000 = 100,000 heat units will be absorbed, and if we vaporize this water, 537 × 1,000 = 537,000 heat units will be required. Thus a total of 722,000 heat units have been absorbed, and will all surely be restored to the atmosphere before that water can again become ice at −10° C. So it appears that water is the great equalizer of temperatures, carrying the summer heat far into the winter to modify its climate, and storing the winter cold (if we may use the expression) with which to refresh the summer season.

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MICHAEL FARADAY (1791-1867).

Professor thirty-four years in the Royal Institution of Great Britain. Induction of electric currents. Effect of magnetism upon polarized light. "The greatest experimental philosopher the world has ever seen." A superior lecturer.

MAGNETISM AND ELECTRICITY

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CHAPTER XXIII

MAGNETS

221. **Magnetite.**—There is found in various parts of the earth an iron ore composed of oxygen and iron (Fe_3O_4), which will attract small bits of iron. This is called magnetite to indicate that it is a magnet. It has also been called loadstone for reasons which will appear later. The small pieces of iron do not cling to all parts of it alike. If a piece of the ore is rolled about among filings of iron, most of them will fall away from the piece of ore when it is lifted, but many will be found clinging to two spots (Fig. 114) situated upon opposite sides or opposite ends from one another. A straight line connecting these two parts is called the axis, and the ends of this line are called the poles of the magnet. It is not necessary that the poles be the ends of the lump. They may be anywhere along the sides, but it is true that they are always opposite to one another. If we suspend the piece of magnetite by a slender thread, it will come to rest with the same one of these poles always north. Let us mark this pole with the letter N and call it the north pole, and the opposite portion we will call the south pole. Because of this property of pointing north, it was originally called loadstone, or the *leading*

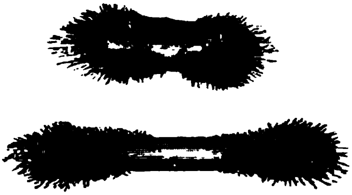

FIG. 114.—Magnets.

stone. The reason for its pointing north and south will be given in section 227.

222. **Steel Magnets.**—If either pole of the magnetite is rubbed several times upon a steel sewing needle, always in the same direction, from one end to the other, the sewing needle will be found to have acquired the property of attracting iron filings at its two extremities. It has become a magnet. Its two ends are the poles, and they will point north and south if free to move.

223. **The Poles of a Magnet.**—If the needle is suspended by a thread, so that it may swing freely in a horizontal plane (Fig. 115), it will be found that the pole of the magnetite which was used to magnetize this needle will attract the pole of the needle which it touched last, but will repel the other. It will also be found that the opposite pole of the magnetite will repel this pole of the needle but attract the other. If a second sewing needle be magnetized in the same way as the first (let us suppose that the north pole of the magnetite is used in each case, and that it is drawn from the eye toward the point of each needle), it will be found that the points of these needles repel each other, and that the ends containing the eyes repel each other, but that the point of each will attract the eye of the other. The law is: *unlike poles attract, and like poles repel.* It will be found that if these needles are allowed to swing freely, without being influenced by any magnet, they will arrange themselves so that their eyes will point north. It will also be found that their eyes will attract the south pole of the magnetite but repel the north pole of the same;

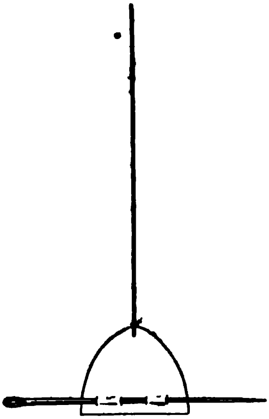

FIG. 115.—Magnetized needle.

also that their points will attract the north pole of the magnetite, but repel its south pole. The poles of these needles may be reversed by rubbing them in the opposite direction with the same pole of the magnetite as was used before, or by rubbing them in the same direction with the opposite pole of the magnetite. These sewing needles are small "bar magnets."

The bar magnets which are on sale have the letter N stamped upon one end of them. If a bar magnet is free to move, this end will point north. If it is brought to the north pole of the magnetite, or the north pole of the sewing needles mentioned above, it will repel, while it will attract the south pole of the same. The reverse is true of the south pole of the bar magnet. Steel magnets are often given the shape of a horseshoe, so that the force of both poles may be applied to the same object.

224. **Magnetic Substances.**—While a large number of substances are affected to a slight degree by very powerful magnets, only steel and iron are visibly affected by magnets of ordinary strength. Soft iron may be magnetized, but will not retain magnetism. The harder the iron, the longer it will retain its magnetism. This is why steel, which is iron hardened by carbon, makes the most permanent magnets. Since both poles of a magnet attract magnetic substances, the way to determine whether a magnetic substance has become a magnet is to find whether there is a repulsion between any part of it and either pole of a magnet.

225. **Influence of Magnets upon Magnetic Substances.**—A magnetic substance when brought near to a magnet is itself always polarized—that is, converted into a magnet. The harder the substance the less this action takes place; but, on the other hand, the more permanent is the result. Soft iron is readily magnetized and as readily loses its magnetism.

If a horseshoe magnet (Fig. 116) is brought near to a bar of soft iron, even though they do not touch, the iron will become a magnet, as will be shown by the way bits of iron, as carpet tacks, will cling to it. With a magnetic needle we may learn that the bar of soft iron is polarized so that its north pole is opposite the south pole of the horseshoe magnet, and its south pole opposite the north pole of the magnet. As soon as the horseshoe magnet is removed the bar of soft iron loses its magnetism, or, at least, retains too little to be recognized by ordinary means. A powerful magnet will reverse the poles of a weak magnet if like poles are presented to each other; for this reason students should be careful about bringing magnets near to compass needles which are not free to move.

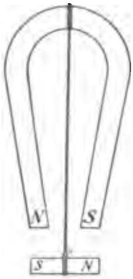

FIG. 116.—Horseshoe magnet polarizing soft iron.

226. **Each Molecule a Magnet.**—To enable us to appreciate what may take place in the needles when we magnetize them, let us arrange some coarse steel filings in a row upon a sheet of paper and draw the north pole of a magnet underneath the paper from left to right. The magnet polarizes each small sliver of steel as it passes by, so that the end of the sliver nearest to the north pole of the magnet becomes a south pole and the more remote end of the sliver becomes a north pole. The repulsion between like poles and the attraction between unlike poles causes each sliver in turn to rise up on end and turn a somersault—the south pole of the sliver always turning toward the north pole of the magnet (see Fig. 117). The result is that after the magnet has passed, the slivers are all arranged in line along its pathway with each north pole pointing toward

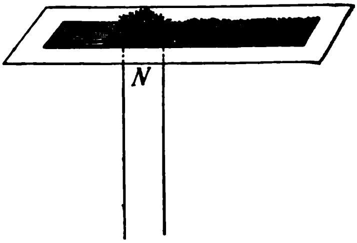

FIG. 117.—A magnet polarizing steel filings.

the left, and inasmuch as they are steel they retain their magnetism, the whole mass of filings acting as a solid bar of steel would—as the sewing needles referred to in section 223—having the pole which is *like* the one used for inducing magnetism at the end first approached, and the *unlike* pole at the end last approached by the inducing magnet. This we think may be analogous to what happens when a bar of steel is magnetized by rubbing it with a magnet, each molecule behaving as these slivers of steel do. By tapping the paper upon which the steel filings are arranged (Fig. 117), after the influence of the magnet has been removed, they will again become disarranged, so that the mass will no longer exhibit north and south poles. So, by hammering a steel magnet, its magnetism is made to disappear. Heating, twisting, bending—anything which might tend to disarrange the molecule—weakens a magnet. If one of the magnetized needles mentioned in section 223 be broken into little pieces—never so small—each piece will have a north and south pole, just as the steel slivers mentioned in the early part of this section; and if the eye of the needle is north pole, the end of each small piece of needle which pointed toward the eye will be its north pole. If the needles could be broken up into molecules, we suppose that each molecule would exhibit the same kind of polarity. Fig. 118 helps us to imagine how the small particles may be arranged with reference to each other. This explains why the iron filings do not cling to the middle portion of the magnet. There the north and south poles neutralize each other, while at the ends they are free to act. The molecules of iron and steel are assumed to be magnets at all times. When they fail to exhibit it they are merely disarranged, and when we magnetize iron or steel we simply cause its molecules to take the proper arrange-

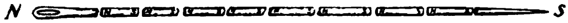

FIG. 118.—New poles formed by breaking a magnet.

ment. The molecules of iron appear to move more freely than those of steel, hence it is more readily magnetized and more easily loses its magnetism. If a piece of steel is hammered or heated while under the influence of a magnet, greater magnetism will be induced in it, as though some such assistance were needed to help move the molecules. When iron is strongly magnetized its length is slightly increased. A faint crackling noise is heard when iron or steel is very powerfully magnetized or demagnetized. If it is magnetized and demagnetized in rapid succession, the metal grows hot, which indicates molecular motion.

227. **The Earth a Magnet.**—If we lay a bar magnet upon the table under a magnetic needle (Fig. 119), the needle will arrange itself so that its south pole will be over the north pole of the bar magnet, and its north pole over the south pole of the bar magnet. The axis of the needle will always be parallel with that of the bar magnet, whatever direction that may take, showing that the force of the bar magnet is greater than that which tends to cause the needle to point north. We have reason to believe that the earth is a great magnet, although not a powerful one. Its magnetic axis is in the same general direction with its geographical axis, and its magnetic poles are in the arctic and antarctic zones. The north magnetic pole of the earth must be unlike the north pole of our needle, because they attract. For this reason it has been proposed to call the end of the needle which points north the north-seeking pole, but the custom of calling it the north pole persists.

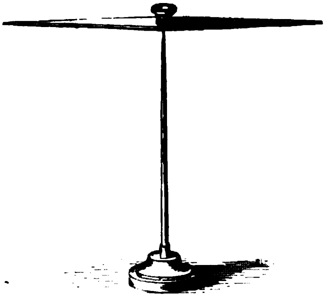

Fig. 119.—Magnetic needle.

If we suspend a magnetic needle so that it is free to swing in a vertical plane (Fig. 120), and move it about over a bar magnet, its north pole will point downward when it approaches the south pole of the bar magnet, and its south pole will dip when it approaches the north pole of the bar magnet. The dipping needle is affected by the earth as by a bar magnet. In the vicinity of the equator it hangs horizontally. As it is moved north, its so-called north pole dips until finally it stands vertical over a point north of North America, but some distance from the geographical north pole, as will be seen by reference to Fig. 121. Likewise, the magnetic south pole does not coincide with the geographical south pole, as may be seen by reference to Fig. 122. From this it is evident that the magnetic needle mounted so as to swing horizontally does not point exactly north and south. Its deviation from that direction is called its *declination*.

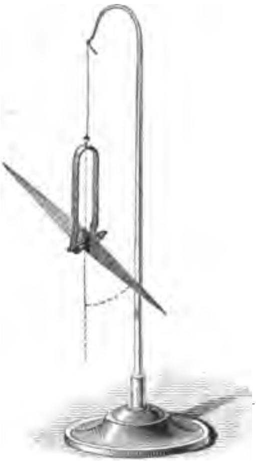

Fig. 120.—Dipping needle.

Figs. 121 and 122 show the lines of equal declination, and the lines of equal dip, or inclination, as it is called, for the whole earth. These figures also show how much the magnetic equator differs from the geographical equator. The magnetic poles of the earth are gradually shifting their position, so that these figures are not correct for all time.

The table below gives the declination and the inclination of the needle at various places for the present year, 1900. The table also gives the intensity of the magnetic force at these various places relative to New York. The absolute force of the earth's magnetism at New York, as expressed in the C.-G.-S. system, is .61 dynes—that is, a force sufficient to move .61 grams 1 centimetre in a second, or 1 gram .61 centimetres in a second.

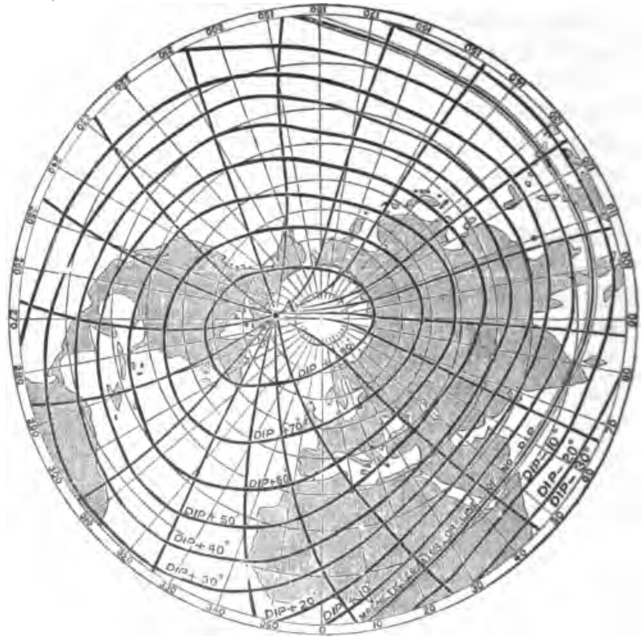

FIG. 121.—Northern Hemisphere.

TABLE OF MAGNETIC DECLINATION, INCLINATION, AND INTENSITY FOR 1900.

	Declination.	Dip.	Intensity relative to that of New York.
New York	9° 12′ W.	70° 6′ N.	1.00
Washington	4° 35′ W.	70° 18′ N.	.98
San Francisco	16° 42′ E.	62° 20′ N.	.89
Cape Town	29° 24′ W.	58° 2′ S.	.59
London	16° 16′ W.	67° 9′ N.	.77
Paris	14° 30′ W.	64° 55′ N.	.77
Berlin	9° 30′ W.	66° 43′ N.	.79
Rome	10° 0′ W.	58° 0′ N.	.74
St. Petersburg	0° 30′ E.	70° 46′ N.	.79

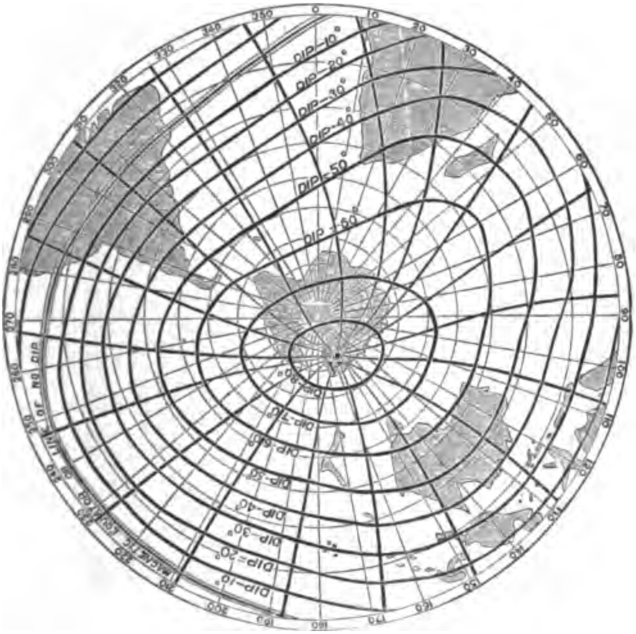

FIG. 122.—Southern Hemisphere.

The declination, dip, and intensity are all gradually changing. The following table exhibits the change in declination at London for three hundred years:

A. D. 1580.........	11° 17′ E.	A. D. 1816........	24° 30′ W.
1622.........	6° 12′ E.	1868.........	20° 33′ W.
1657.........	0° 0′	1880.........	18° 40′ W.
1705.........	9° 0′ W.	1890.........	17° 26′ W.
1760.........	19° 30′ W.	1900.........	16° 16′ W.

228. **The Mariner's Compass.**—This is merely a magnetic needle free to move in a horizontal plane. It is attached to the underside of a card (Fig. 123). This is inclosed in a box called the binnacle. A fixed line shows the direction of the keel of the ship, while the card, being carried about

by the compass needle, shows always the deviation of the ship's course from a north-and-south direction. This deviation is measured in "points," each point being 11¼ degrees. Of course it is necessary for the mariner to correct his reading for the declination of the needle, which he must determine from tables and charts.

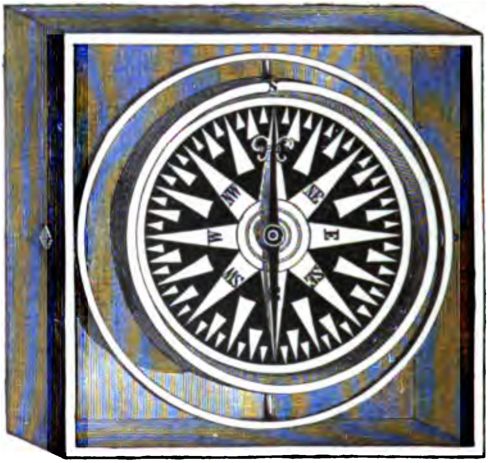

FIG. 123.

The mariner's compass appears to have been used by the Chinese in very crude form long before it was known to the Western world. It was discovered independently in Europe, perhaps in the twelfth century, but it took several centuries for it to reach its perfection. It is difficult to estimate the great value it became in the fifteenth century in enabling mariners to extend the boundaries of the known world.

From the fact that the earth is a magnet, we might expect to find that it would induce magnetism in magnetic substances, and this we find to be true. This accounts for the magnetism of the ore called magnetite. A compass needle brought near to the base of an iron pillar will have its southseeking pole attracted; if it is carried to the top of the pillar, its north-seeking pole will be attracted. From the fact that the inclination of the dipping needle is over 70° in New York, we might expect to find that the bottoms of iron pillars would become north-seeking poles by the induction of the earth, and such is the fact. Thus it happens that no magnetic substance is ever entirely free from magnetism.

229. **The Law of Inverse Squares.**—The magnetic force, like gravitation, heat, light, and electric attractions and repulsions, varies inversely as the square of the distance. Fig. 124 explains this. The force proceeding from *F* in all directions as the radii of a circle, would produce a certain effect at *a*, and only one quarter of that effect at *c*, which is twice the distance of *a*; and one ninth the effect at *c′*, which is three times the distance of *a*; and one sixteenth the effect at *c″*, which is four times the distance of *a*. The areas at *c*, *c′*, and *c″*, being respectively 4, 9, and 16 times as great as that of *a* (see Geometry), the force must distribute itself accordingly; but these numbers are the squares of 2, 3, and 4 respectively; hence if we square the distances to be compared, we shall get the rate at which these forces diminish at those distances. The usual form of statement is: *The force varies inversely as the square of the distance.*

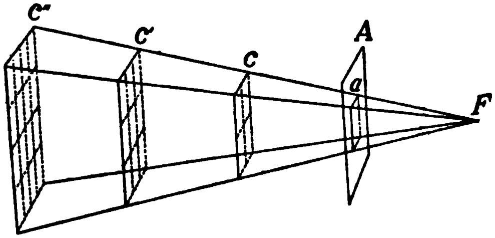

FIG. 124.—Law of inverse squares.

This helps us to answer the question, Why should a sliver of iron move toward a magnet? The magnet polarizes the sliver of iron, so that the pole of the sliver nearest to the pole of the magnet is *unlike* it, and therefore they attract each other; the farther pole of the sliver is *like* the pole of the magnet, and therefore they repel each other. But the attraction is greater than the repulsion, because the pole which attracts is nearer than the pole which repels, hence the object, if light, and if very near, is moved toward the magnet.

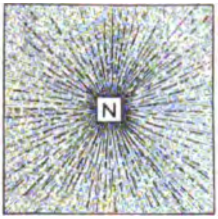

FIG. 125.

Note that magnets in order to exert any large force must be *very* near to the magnetic substance.

230. **Lines of Magnetic Force.**—Fig. 125 shows how lines of force go out from the pole of a magnet. Figs. 126, 127, 128, and 129 show how these lines are affected by the proximity of other poles. These lines of force may be mapped out upon paper by placing the magnet underneath and distributing slivers of iron over the surface. Each sliver will become polarized and act like a small magnetic needle. A fuller illustration, however, will be obtained by moving a small compass around in the vicinity of magnets placed as in the figures. By means of the compass needle

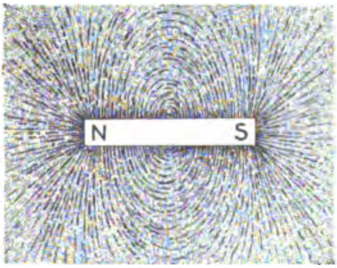

FIG. 126.

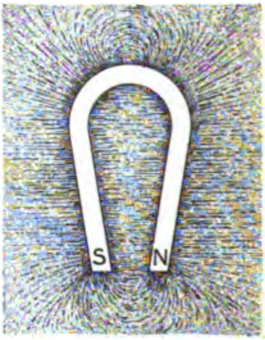

FIG. 127.

we get the lines in three dimensions of space, rather than in the one plane alone of the paper.

We shall learn in the chapter upon Current Electricity that these lines of magnetic force may exist without a magnet. We speak of the region penetrated by these lines of force as a magnetic field, and we are able to produce, by means of electricity, a magnetic field without the presence of any magnetic substance. If soft iron be brought into this field, produced by an electric current, it becomes a magnet, as when brought near a steel magnet. We speak of it then as an electro-magnet. This subject will be treated more fully under Electricity (Chapter XXV). The reasons for the earth being a magnet will also be found there.

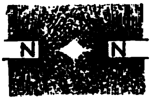

FIG. 128.

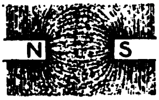

FIG. 129.

Lines of magnetic force penetrate with perfect ease through any substance except iron. The experiments represented by Figs. 117 and 125–129 would not be successful if sheet iron were used instead of paper. Glass, wood, or anything else may be used, provided it is thin, so as to allow the magnet to come very near to the iron filings.

CHAPTER XXIV

STATIC ELECTRICITY

231. **Electrification.**—Experience teaches us that in cold weather many things are easily electrified: one's hair, when it is brushed; a cat's fur, when it is rubbed; a rubber penholder or comb, when dropped upon the floor; our own bodies, when we rub our feet upon the carpet. The electrification is shown by attraction and repulsion of light objects, crackling sounds, and sparks. All bodies are capable of being electrified, under proper conditions, and any object which is electrified exhibits attraction and repulsion for all other forms of matter. In this respect electricity appears to be very unlike magnetism, which affects iron alone. The objects which we choose as suiting best our purpose for experiment are sealing wax and glass. We get the best results when we rub the sealing wax with flannel and the glass with silk. Pith balls are chosen for the experiments, simply because they are very light, and therefore move more readily under the influence of the slight forces with which we deal. It is well to gild the pith balls for reasons which will appear in section 234.

232. **Two States of Electrification.**—Pith balls which have been electrified by contact with the electrified sealing wax repel each other, likewise pith balls which have been electrified by contact with the electrified glass repel each other; but pith balls which have been electrified, one by contact with the sealing wax, and the other by contact with the glass, attract each other. The law is: *Bodies with like*

kind of electrification repel, those with unlike kinds attract. We prefer to speak of kinds of electrification rather than kinds of electricity, because we do not believe there are two kinds of *electricity.* We shall speak of glass as being *positively* electrified, and sealing wax as *negatively* electrified. The flannel which is rubbed upon the sealing wax becomes *positively* electrified, and the silk which is rubbed upon the glass becomes *negatively* electrified. Pith balls, when they come *in contact* with an electrified body, acquire the same kind of electrification as that body. The way to determine whether a body is electrified, or which kind of electrification it may have, is to present it to pith balls electrified with each kind; repulsion, not attraction, determines the matter. One's hair "flies" when brushed in cold weather, because bodies having like kind of electrification repel each other.

233. **Static Electricity and Electric Currents.**—The titles of Chapters XXIV and XXV, *Static Electricity*, and *Electric Currents*, are not intended to convey the impression that there is more than one kind of electricity, but that electricity may manifest itself in different conditions. The present chapter treats of electricity in a state of tension. The analogous term in water pressure is *hydrostatic*, which refers to the pressure of water at rest. But electricity may flow, and we have conductors for it. Whether the flow of electricity through a conductor is like that of water, or like that of heat, we may not, at this point, discuss intelligently. Chapter XXV treats of *Electric Currents*, but their consideration must also enter, to a slight extent, into this chapter.

234. **Conductors.**—In Fig. 130 *b c* represents a copper wire attached at each end to silk threads *a b* and *c d.* At *e* two pith balls are suspended upon silk threads, and at *f* two pith balls are suspended by very fine copper wire. Before the experiment begins, the pith balls at *f* hang in contact with one another, as those at *e.* If now we touch

an electrified body to any part of the copper wire *b c*, the electricity flows through the copper wire to the pith balls at *f*, and, each having the same kind of electrification, they repel, as represented in the figure. Copper is a conductor of electricity. Dry silk is not a conductor; or, as we say, it is a *non*-conductor. Hence the pith balls at *e* do not separate, because they are hung upon silk threads. The silk threads, *a b* and *c d*, are used to prevent the electricity from flowing away from the pith balls at *f*. They are called insulators—another word for non-conductors. If we moisten either *a b* or *c d*, the pith balls at *f* will fall together again, showing that the electricity flows away through moist silk. If the silk threads which suspend the pith balls at *e* are moistened, while *a b* and *c d* are dry, an electrified body touching *b c* will cause the pith balls at *e* to separate, as well as those at *f*. There are no perfect conductors, and there are no perfect insulators; hence electricity leaks away from all electrified bodies, and it is difficult to keep them charged long. Dry air is a very good insulator, but the moisture in the air is a good conductor. Hence these electrical experiments work best in cold weather when there is less moisture in the air. It is well to remember that the moisture of the breath may interfere with our experiments.

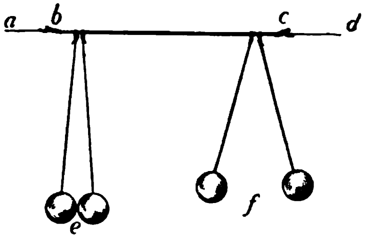

Fig. 130.

A telegraph wire is a *conductor* of electricity, and the glass knobs upon telegraph poles are *insulators*.

In the table which follows, the best conductors are at the head of the list. Electricity produced by friction will force its way quite readily through all those in the first half of the list. They may, therefore, all be called conductors, although they differ very widely among themselves in this respect. Copper conducts more than a million times as well as water. Those in the last half of the list may be called insulators, the poorest conductors being at the end of the list:

Copper.
Iron.
Carbon.
Dilute sulphuric acid.
Water.
Human body.
Linen.
Cotton.
Wood.
Paper.
Air.
Silk.
Sealing wax.
Glass.
Hard rubber.
Porcelain.
Shellac.

The chief difference between electricity produced by friction, as in this chapter, and that produced by chemical action, as in the next chapter, is that although friction produces exceedingly small quantities of electricity, it is vastly more capable of pushing its way through resistance; and hence some things which are called conductors in this chapter will be considered insulators in the next. Only the first four substances mentioned in the above list will be considered good conductors in the next chapter, and only the last six are to be considered really good insulators in this chapter.

We may now see why we chose sealing wax and glass. It is because, being good insulators, they retain their electrification, while metals and other conductors lose their electrification as fast as it is produced. This, however, may be obviated by putting glass handles upon metals. Of course, the electricity spreads all over the metal substance, while with a non-conductor it remains in those parts where it is produced. This may be shown by rubbing sealing wax or hard rubber, in spots, with flannel, and then laying it upon some granulated sugar. It will pick up the sugar on those spots only which have been rubbed. It will now appear why we proposed to gild the pith balls in section 231. The electricity will thus flow all over the surface, and they will carry a much larger charge. Dry pith is a poor conductor.

235. Induction, the Influence of Electrified Bodies upon Neighboring Objects.—Electrified bodies, like magnetized bodies, exert an influence upon objects near them. One difference, however, is that an electrified body exerts its influence upon all kinds of matter alike; whereas magnets affect iron only. In the case of both magnetism and electricity, we believe that the power to influence objects without contact is due to the ether, which, by its waves, may produce heat, light, electric and magnetic phenomena. Indeed, many think that electricity is the ether.

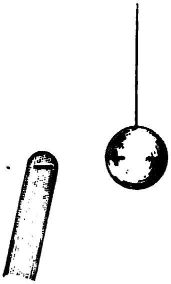

FIG. 131.

When an electrified body is brought near any neutral substance, without touching it, that substance is, as we might say, polarized. The part nearest to the electrified body exhibits the opposite kind of electrification, and the more remote part exhibits the same kind of electrification as that of the inducing body. This apparent action at a distance is known as *induction.* It is not, however, action *at a distance,* but action *through the medium of the ether.*

We may now see why there is an attraction between neutral bodies and electrified bodies, and why, if either of them is very light and free to move, they will come together. Fig. 131 represents an electrified stick of sealing wax held near to a pith ball, which it has not yet touched. Its influence *polarizes* the pith ball. The side nearest the sealing wax becomes positively charged, and the farther side becomes negatively charged.

Since bodies with unlike kinds of electrification attract, and those with like kinds repel, the pith ball is both attracted and repelled; but the law of inverse squares, as stated in section 229, holds for electricity as well as magnetism. Because of the difference in distance, the attraction is greater than the repulsion, and the pith ball moves toward the sealing wax. As the distance between them grows less, the difference between attraction and repulsion grows rapidly greater. When the space between the sealing wax and the pith ball is about equal to the diameter of the ball, the attraction will be four times as great as the repulsion. When the distance becomes one quarter as great, the attraction will be sixteen times as great as the repulsion, etc. Thus the pith ball moves faster and faster as it approaches the electrified body. When it touches, there is a flow of electricity from the neutral body to the other, until they are in the same state. Then repulsion begins and the pith ball flies off from the sealing wax. It is now negatively charged, and will act toward a neutral object as the sealing wax acted toward it. If it is brought near to a neutral body it polarizes it, so that attraction is greater than repulsion between them. If the neutral body is heavier, or is not free to move, the pith ball will move to it. If the neutral object should be a second pith ball, of equal weight with itself (Fig. 132), they will move equal distances toward one another. When they touch there will be a flow of electricity from one to the other, and they will then be exactly alike, and repel. The second ball will produce exactly the same effect toward neutralizing the first ball as the first does toward electrifying the second. Hence, every time an electrified conductor charges another body, it tends to neutralize itself. This is different from magnetism. A magnet is not at all weakened by magnetizing other pieces of iron. In the next two sections we shall see how an electrified body may enable us to electrify any number of other bodies, without itself becoming discharged at all.

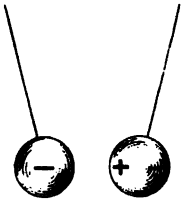

FIG. 132.

236. **By Induction a Polarized Body may receive a Charge from a Neutral Body.**—Fig. 133 represents an electrified stick of sealing wax held near to a neutral pith ball, so as to influence it without contact. The pith ball is polarized and drawn toward the sealing wax, as explained in section 235. If now the sealing wax should be removed, the pith ball would return to its former neutral state; but if, while it is polarized under the influence of the sealing wax, a neutral object, as for example one's finger, is allowed to touch the pith ball and after that the sealing wax is removed, the pith ball will be found to be positively charged. While we must guard against thinking that we know just what happens, it is interesting to learn what those who have thought much about these things have conjectured. Benjamin Franklin conjectured that it might be something like this: The electricity of the pith ball may have accumulated, under the influence of the sealing wax, in the under part of the ball, leaving the upper part rather destitute. This fact he indicated by the + and − signs. When another object touches the pith ball, electricity flows in to fill the vacancy, and now when the sealing wax is removed the ball has more than the normal charge.

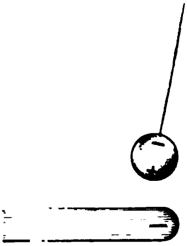
FIG. 133.

237. **The Electrophorus.**—This is a further illustration of the subject presented in the last section. A jelly-cake tin with sealing wax melted in it, and hardened into a layer from an eighth to a quarter of an inch in thickness, makes a satisfactory form of electrophorus. It serves as a convenient means for electrifying other objects, without losing its own charge. The sealing wax is rubbed with flannel. This, by induction, enables us to electrify a neutral disk, from neutral objects, an indefinite number of times. Another jelly-cake tin, a little smaller in size, serves well for the neutral disk. This disk when charged is handled by

means of silk threads for insulation (see Fig. 134). The sealing wax, being a non-conductor, does not impart electricity to the neutral disk in sufficient quantities to charge it, as a stick of sealing wax may charge a pith ball. Indeed, the points of contact between the sheet of wax and the neutral disk are extremely slight. The result is that the metal disk is polarized while resting upon the wax, as shown in Fig. 135, where *a b* represents the metal disk and *c d* the sealing wax. If now one touches the disk with his finger, while in this condition, the disk becomes positively charged in the same manner as the pith ball described in section 236. If the disk is lifted by the silk threads, it will carry away a positive charge as many times greater than that which a pith ball would carry as its area is greater than that of the pith ball. The process may be repeated an indefinite number of times without again rubbing the wax with the flannel. The disk is charged each time by electricity from the earth flowing through the body of the operator and off the finger with which he touches the disk. If this charged disk is brought near to any neutral object, the discharge is marked by a spark of considerable length. This spark will light the gas if the disk is presented to a gas jet. It will explode the mixture of oxygen and hydrogen in the eudiometer (see Fig. 1, page 9). If one brings a finger to this charged disk after it is removed from the influence of the sealing wax, which, as we say, holds the charge "bound," he will experience, when the spark passes, a slight pricking sensation. We may, however, store, so to speak, several

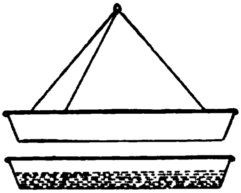

FIG. 134.

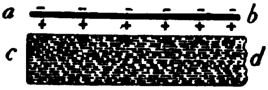

FIG. 135.

of its charges in a condenser, described in the next section, so that one will feel a larger shock, when the charge is taken all at once, through the body.

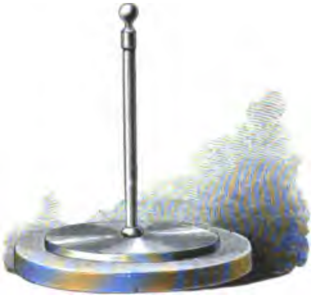
FIG. 136.—Electrophorus.

A very common form of electrophorus is shown in Fig. 136, which consists of a cake of hard rubber and a metal disk with a glass or hard-rubber handle.

The electrical machines in common use (see Fig. 137) work upon the same principle as the electrophorus. Rotating the glass disk accomplishes precisely the same thing as carrying a charge by means of the metal disk of the electrophorus and delivering it to some object. The machine delivers a continuous flow of charge through a conductor. These machines also have attached to them condensers, described in the next section.

238. **Condensers.** — A large beaker of chemical glassware makes a good condenser. The inside and outside are gilded, or covered with tinfoil, to about two inches from the top. Suppose this is held upon the hand, as shown in Fig. 138, and the electrified cover of the electrophorus is brought to the outer coating. The outer coating becomes positively electrified, and this polarizes the inner coating by induction. The positive electrification is discharged through the hand, leaving the inner coating nega-

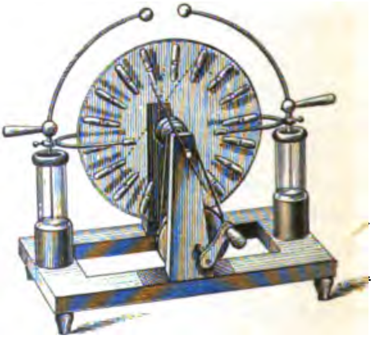
FIG. 137.—Electrical machine.

tively electrified. If now the other hand is brought to the outer coating, the coatings of the beaker neutralize each other by discharging through the body. If the cover of the electrophorus is discharged into the outer coating of the beaker several times, we find the shock produced by the discharge proportionally increased. Twenty sparks from the electrophorus will charge the condenser sufficiently to send a considerable shock through a class of thirty or forty pupils with hands joined. Condensers have a variety of shapes. The most convenient form is that of the Leyden jar, illustrated in Fig. 139. The name is derived from the city of Leyden in Holland, where it was invented in the year 1746.

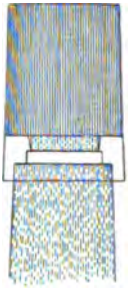

FIG. 138.

239. **Lightning.**—The earth, the air, and the clouds constitute a natural condenser like a huge Leyden jar. The clouds constitute one coating, the earth the other, and the atmosphere represents the glass insulator between the two. This natural condenser becomes charged in various ways. Evaporation is perhaps one cause of electrification. If the vapor is positively charged, as it accumulates in the clouds, it induces a negative charge in objects upon the earth's surface, immediately underneath the clouds. Lightning is the spark

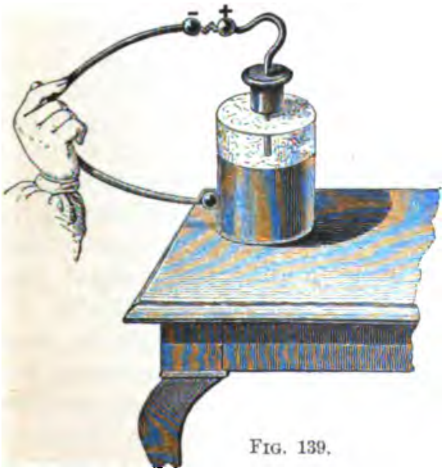

FIG. 139.

which attends the discharge of this natural condenser. It frequently happens that the vapor of one cloud is positively charged with reference to that of another, and it is probable that the lightning discharge between two clouds is of much more frequent occurrence than that between cloud and earth.

240. **Electrical Distribution—Effect of Points.**—If the electrified body is a non-conductor, the electrification appears only in those spots where it was produced; but if the body is a conductor, the charge spreads itself over all the surface. The opposite extremities are not poles, as in the case of a magnet, nor is the intervening part neutral. The charge, however, whether positive or negative, affects the outer surface only, and this gives us trouble with Franklin's conjecture, mentioned in section 236. The fact is, that if the gilding of an electrified pith ball should fall off, it would remove all signs of electrification, whether + or −, from the pith ball. This is shown by an experiment with the apparatus illustrated in Fig. 140. A neutral ball upon an insulated support is covered with two metal hemispheres. It is electrified either before or after the hemispheres are put on; but when the hemispheres are removed by the glass handles they alone are found to be electrified. The sphere itself is left in a neutral state. If an insulated tin cup is electrified, no sign of a charge will be found inside the cup, but only upon the outer surface. The charge is also found

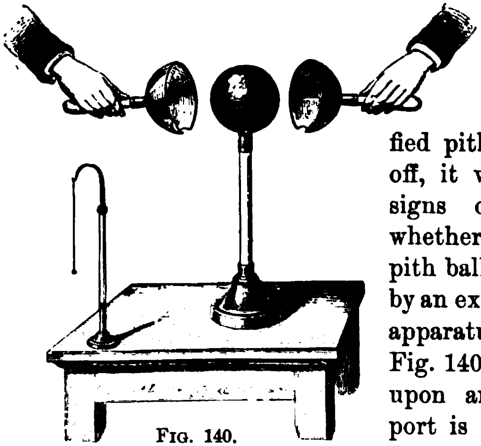

FIG. 140.

to be most intense upon projecting portions, as the handle of the cup. If an egg is insulated and electrified the greatest intensity of charge will be found upon the small end of the egg. If we construct an object egg-shaped, but with the small end very much drawn out, as in Fig. 141, the difference between the intensity of the charge upon this prolongation and the rest of the surface will be very marked. If the small end is made into a sharp point, the tension of the charge will be increased at this point to such an extent that the electricity which, as was said in section 234, always leaks away to some extent, will disappear rapidly. Hence, objects like the pith ball, which should retain a charge, are made as round and smooth as possible. This accounts for the many knobs upon electrical apparatus. When points are used, as, for example, the "*combs*" on the electrical machine (see Fig. 137), they

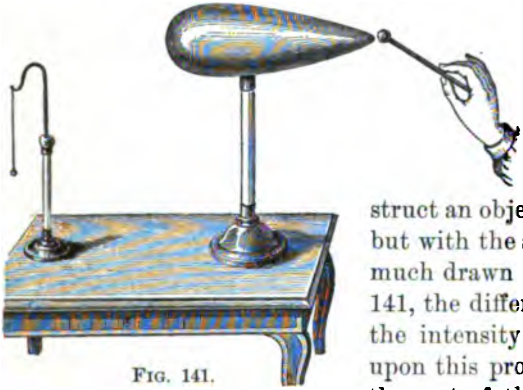
FIG. 141.

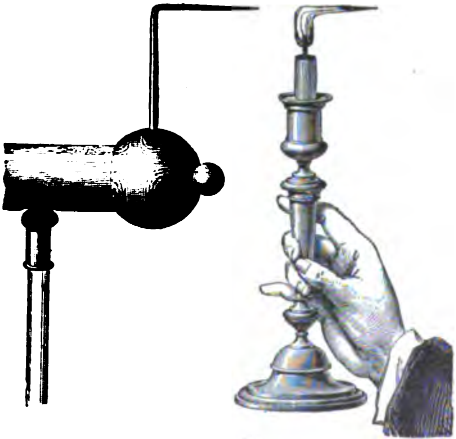
FIG. 142.

are to facilitate the discharge from one portion of the apparatus to another. If a portion of the electrical machine has a point projecting from it, as shown in Fig. 142, it will create a sufficient breeze to blow out a candle. This may be accounted for by supposing that the particles of air are electrified and thrown off at this point, like pith balls, in a stream. If the points are arranged at the extremities of the spokes of a wheel, as shown in Fig. 143, the wheel will rotate as a lawn sprinkler, which throws off streams of water from its arms. As has been already stated, an electrified cloud induces the opposite state of electrification in that portion of the earth which is immediately underneath it. Mountain peaks, spires of buildings, lightning rods, masts of ships, etc., like points upon electrical apparatus, facilitate the discharge between the earth and the clouds. If an electrical machine is operated in a dark room, a pale light is seen to stream from sharp points upon the machine. This phenomenon occurs in Nature on a grand scale. Sailors notice pale flames streaming from the tips of the masts when a strongly electrified cloud is passing over. This is called by them St. Elmo's Fire.

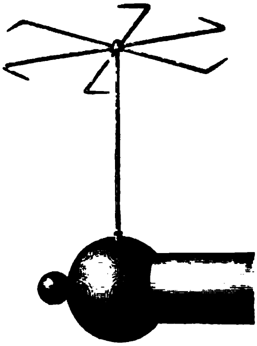

FIG. 143.

CHAPTER XXV

ELECTRIC CURRENTS

I. GENERATORS OF ELECTRIC CURRENTS

241. **Sources of Electric Currents.**—Observe that we do not say sources of electricity. That would be inconsistent. Assuming electricity to be identical with the ether, we can neither create nor destroy it. But electricity may be set in motion; this flow of electricity from one point to another is the subject of this chapter, and we may properly begin with the sources of the current. The discharge of a Leyden jar, or other electrified body, through a conductor, is a current of electricity. If we connect the two knobs of the electrical machine represented in Fig. 144 by a copper wire, a constant current of electricity flows through the wire while the machine is operated. The current produced by this machine is, however, extremely slight in quantity, and is therefore of little use, although, as was stated in section 234, it has exceedingly high tension and can push its way through poor conductors. A few analogies will help to make clear the distinction between high-tension and large-quantity currents.

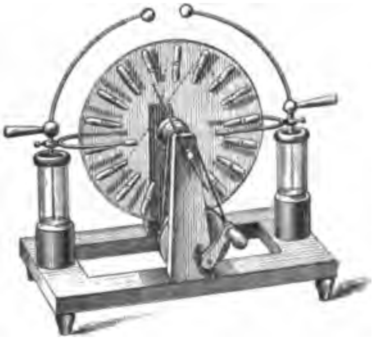

FIG. 144.—Electrical machine.

The current which we get from the electrical machine mentioned above may be compared with a stream of water coming through a pin hole in the bottom of a very deep tank which is full of water. Although the " head of water " may be very great, the quantity is too small to turn a mill wheel. Or it may be compared with a pile driver weighing only one ounce, but raised to a great height. It falls with great velocity, but with too little momentum to move the pile. Or it may be compared with a cup of water heated to the boiling point. Its temperature is very high, but the quantity of heat is too small to modify the climate, or to heat a house or to cook a dinner. In these analogies *water pressure*, *velocity*, and *temperature* represent *electric tension*. In the present chapter we shall discover means for producing electric currents in larger quantities, although the tension will be quite low and they will not flow through much resistance. By way of analogy they may be compared with the flow of a large stream of water, having only a few feet of fall but capable of operating a water wheel. Or they may be compared with a pile driver of considerable size, capable of driving a pile by falling only a few feet. Or they may be compared with a large body of water slightly warm, but able to modify the temperature of surrounding objects for a long time by reason of its large quantity of heat.

We shall present in this chapter three sources of current—*chemical action*, *mechanical motion*, and *heat*—and these forms of energy are transformed into current by means of the *battery*, the *dynamo*, and the *thermopile* respectively. Turning back for a moment to the general conception of work, it will be recalled that work is the overcoming of resistance through space, and involves both motion and something to be moved. Energy, or the power to do work, is only possible, therefore, when we have matter in such a position that it is capable of motion. This means inequality of condition, and therefore possible exchange. The weight on top of the pile driver represents stored-up work simply because there is a lower level to which the weight may fall. The steam in the boiler represents stored-up work simply because there is a lower temperature to which the steam may fall. All matter at the same level, all bodies at the same temperature, represent no possible interchange, and therefore no available energy. Lift some of the matter above the general level, and at once we have potential energy. Heat some of the bodies above the general temperature, and we have available energy. The water upstream turns the mill because of the lower level downstream. Applying this thought to electricity, we see that so long as the electric level is undisturbed, there is no electric current. The universe is as full of electricity as the ocean is of water, but just as the ocean must be lifted up by evaporation and precipitated in rain upon the hills before it is available as a water power, so to make electricity available as a source of energy we must disturb its level, and we must provide a suitable channel through which the equilibrium may be brought about. All devices for producing electric currents may be regarded as devices for changing the electric level, and all conductors as channels for bringing about equalization of level. If the difference of level is temporary, the current will be temporary; but if the difference of level is constantly maintained, and the channel remains the same, the current will also be constant.

242. **Electric Potential** is the term applied to electric level. Currents flow from a place of high potential to a place of low potential. In case the potential is equal, there is no flow of current. The production of current is practically the process of maintaining a difference of potential. This is also called *electro-motive force*, abbreviated to E. M. F., or simply E; the unit for the measurement of which is called the *volt* (254), a name derived from Volta, the inventor of the voltaic cell.

243. **The Voltaic Cell** (Fig. 145) is a machine for maintaining a constant difference of potential through constant chemical action. In its simplest form it consists of two metals joined by a conductor and moistened by some liquid that will dissolve one of them. A jar of water acidulated with sulphuric acid, H_2SO_4, and containing a strip of copper and a strip of zinc, constitutes a simple voltaic cell. On joining the copper and the zinc by a wire, a current flows from the one to the other. Meanwhile the zinc is being acted upon by the acid, and is passing into solution as zinc sulphate, $ZnSO_4$, while bubbles of hydrogen, H, appear on the copper plate. The chemical action is as follows: $Zn + H_2SO_4 = ZnSO_4 + 2H$. The source of current here is the chemical action between the zinc and the acid. The copper remains unchanged, but in its absence we should have no current; we should have the same chemical reaction, but the physical product would be heat. The solution would become very hot. The copper largely prevents this production of heat, and causes the energy to appear as electric current. The zinc, being the metal acted upon, and the apparent source of the difference of potential, is termed the electro-positive metal, while the copper is the electro-negative metal.

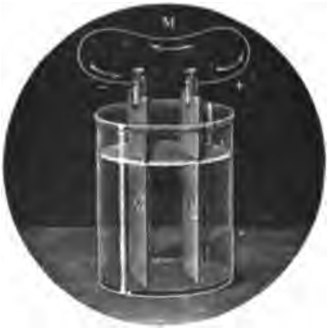

FIG. 145.—The voltaic cell.

The galvanic cell consists, then, of—

1. The electro-positive metal.
2. The electrolyte, or substance which will produce a chemical reaction with the positive metal.
3. The electro-negative element.

We may substitute for zinc any other metal that will be acted upon by the electrolyte chosen. Instead of the sulphuric acid, we may use any other substance that will produce a chemical change with the electro-positive metal. And, finally, the electro-negative element may be any conductor, such as platinum or carbon—that is, insoluble or less soluble than the electro-positive metal. It need not itself be a metal.

By means of a condensing electroscope, the upper end of the carbon can be shown to be positively but very feebly charged, and the upper end of the zinc to be likewise negatively charged by a conductor, wire or other. In order that there may be a current of electricity, there must be a complete circuit—that is, the upper ends of the carbon and the zinc must be connected. We think that the current flows through the wire from the carbon to the zinc, and through the solution from the zinc to the carbon.

For convenience in introducing various pieces of apparatus into the electric circuit we have two wires, one connected with the carbon and the other connected with the zinc. The free ends of these wires are called *poles.* The free end of that connected with the carbon is called the *positive* pole, and the free end of the other wire is called the *negative* pole. In short, any point in the circuit is positive with reference to any other point in the circuit *toward* which the current flows, and negative with reference to any other point in the circuit *from* which the current flows. So that in the solution the zinc is positive with reference to the copper or carbon; but outside of the cell the wire connected with the copper or carbon is called the positive pole or the *anode*, while that connected with the zinc is called the negative pole or *kathode.*

244. **The Electro-Chemical Series.**—Since we need only chemical action and a suitable conductor, the choice of materials for a galvanic cell covers a wide range. But what we are working for is a strong, constant current of electricity, and so our choice of material must practically be limited to combinations that will give this result. If we arrange the

available chemical elements in a list according to their properties, putting those first which are the most readily oxidized, we shall find that the strongest current results when two widely separated elements are chosen. Such a list would stand as follows:

+Sodium.
Magnesium.
Zinc.
Lead.
Tin.
Iron.
Copper.
Silver.
Gold.
Platinum.
−Carbon.

The alkali metals, such as sodium, and the alkaline-earth metals, such as magnesium, are practically ruled out on account of the too great energy of their chemical affinity and their expense. Zinc, therefore, is the electro-positive metal usually chosen. At the other end of the series copper and carbon are the electro-negative elements most frequently used. But any element in the list is electro-positive with respect to the element following it, and electro-negative to the one before it. The order of the list also represents the heat-producing power of the elements. This is very significant when we remember that the chemical action yields heat when the conditions are such that it may not yield a current, as when the copper or carbon is wanting.

245. **Local Action and Polarization.**—The zinc-carbon-sulphuric acid cell just described is not a very practical machine, for two reasons: the zinc wastes away when the cell is not in operation, and the current is far from constant. The waste is due to *local action*, and the *unconstancy* to *polarization*.

Local Action.—If chemically pure zinc be used, it will only dissolve when it is in connection with the carbon and the current is flowing. But the zinc of commerce is far from pure. It contains appreciable quantities of iron and carbon, and dissolves in the acid even when not connected with the copper. This is due to local action between the zinc and the iron or other impurity by which we have internal currents set up, and, as a result, constant waste. It may be avoided by amalgamating the zinc. A few drops of mercury are rubbed over the clean and acid-moistened plate of zinc, forming a surface amalgam. The impurities do not dissolve in the mercury. Hence the plate acts like pure zinc, and the amalgam goes on forming during the action of the cell, just as rapidly as the zinc is dissolved out by the acid.

Polarization is a more serious evil. The hydrogen liberated by the chemical action of the zinc and sulphuric acid is electro-positive, and hence gathers upon the carbon or electro-negative plate. This not only acts as an insulator of the negative plate from the current—the gas not being so good a conductor as the solution—but it lessens the difference of potential between the two plates. Indeed, the hydrogen, if it should completely cover the carbon plate, would change it from an electro-negative to an electro-positive plate. The current in consequence grows weaker and weaker, the carbon plate is said to be polarized, and can only be restored to full action by the removal of the hydrogen. Different methods have been suggested for the prevention of polarization, and have given rise to our present large number of kinds of voltaic cells, some of which are mentioned in the following list:

246. Some Typical Cells.

	E. M. F. Volts.
Bichromate cell	2.1
Bunsen cell	1.9
Leclanché cell	1.4
Daniell cell	1.05
Gravity cell	1.05

In the bichromate cell (Fig. 146) the zinc plate is suspended between two plates of carbon, and, being attached to an adjustable rod, may be drawn up into the neck of the bottle and quite out of the solution when the cell is not in use. Chemical depolarization depends in all cases upon the action of an oxidizing agent. The hydrogen is thus changed into water, H_2O. In the bichromate cell the oxidizing agent is bichromate of sodium, $Na_2Cr_2O_7$. About one pound is added to a gallon of water and a pint of sulphuric acid. When the solution is fresh it is bright red, but gradually turns dark and green from the reduction of the bichromate. The capacity of the jars varies from half a pint up to a gallon. The bichromate cell has long been a favorite one for lecture use, as it gives a powerful current and is always ready.

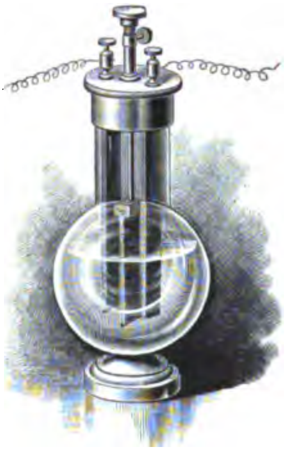

FIG. 146.—The bichromate cell.

The Bunsen cell (Fig. 147) is a double-fluid cell. The electro-negative element is carbon, immersed in the oxidizing agent, strong nitric acid, HNO_3, contained in an inner porous cup. The zinc is amalgamated, and is in the form of a cylinder open at both ends. It surrounds the porous cup, and stands itself in dilute sulphuric acid: The hydrogen liberated by the solution of the zinc passes through the porous cup, but fails to reach the carbon, because it meets the nitric acid and is oxidized to H_2O with the liberation of red fumes of nitrogen peroxide, NO_2. The cell

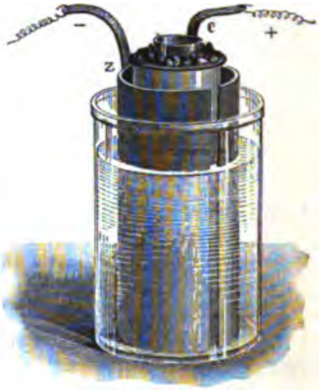

FIG. 147.—The Bunsen cell.

is strong and constant, but the peroxide fumes are corrosive and poisonous.

The Leclanché cell (Fig. 148) is a single-fluid combination in which zinc and carbon are immersed in a solution of ammonium chloride, NH_4Cl, and polarization is prevented by surrounding the carbon with a packing of mixed carbon and black oxide of manganese, MnO_2. The zinc may be in the form of a pencil, or a cylinder surrounding the carbon. The action is very simple. The zinc forms a soluble double chloride of zinc and ammonia, while free hydrogen and ammonia gas, NH_3, pass toward the carbon. But the oxide interposes, taking care of the hydrogen, and the ammonia gas escapes into the air. The oxide of manganese is itself reduced to a lower oxide, and must in time be removed. These cells are used in almost every house for ringing electric bells. Their great virtue is that no chemical action takes place in them except when the electric current is flowing. Hence they are known as "open - circuit" batteries. For ordinary household purposes they may last a year or two without any replenishing of parts.

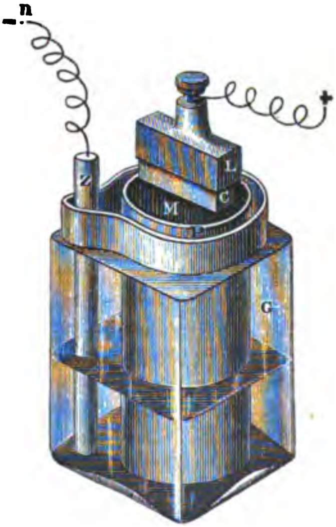

FIG. 148.—The Leclanché cell.

The Daniell cell introduces an entirely new method of preventing polarization. A copper plate is immersed in a solution of copper sulphate, $CuSO_4$, in the outer glass jar, and zinc is immersed in sulphuric acid in an inner porous jar. The hydrogen which is set free by the action of the sulphuric acid upon the zinc passes through the porous cup, but instead of collecting upon the copper plate it decomposes the copper sulphate, forming H_2SO_4 and setting the copper free which is deposited upon the copper plate. The copper, being electro-negative, does not change the character of the negative element, and the current therefore is almost constant. The outer liquid is maintained a saturated solution of copper sulphate by crystals of the salt.

The gravity cell (Fig. 149) is a modification of Daniell's, and dispenses with the porous cup. The copper rests on the bottom of the jar. A saturated solution of copper sulphate completely covers the copper, extra crystals of the sulphate being placed in the bottom. The zinc is suspended from the top of the jar, about four inches above the copper. It is surrounded by a solution of zinc sulphate, which, being less dense, floats on top of the heavy copper sulphate solution. The cell gets its name from the fact that gravity replaces the porous cup in keeping the two solutions apart. The zinc sulphate increases as the zinc wastes away, and must be removed from time to time. The copper sulphate is used up, and must be renewed by dropping fresh crystals into the bottom of the jar. As the copper sulphate forms a deep-blue solution, one can always tell when more crystals are needed. The blue color should extend above the copper, but never quite reach the zinc.

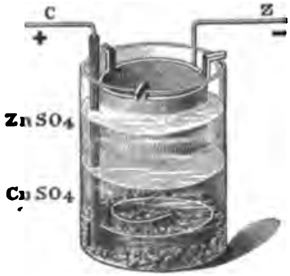

FIG. 149.—The gravity cell.

On account of its convenience, economy, and constancy, the gravity cell is used almost entirely for telegraphic work. One may see them at nearly every railway station.

The number of actual and possible cells is legion. We have described only those which are to-day most important and most frequently met. They are all simple machines for maintaining a more or less constant difference of potential between two points, and consequently setting up an electric current.

247. **The Battery of Cells.**—When several cells are joined together, they form a voltaic *battery.* If the positive metal of one cell is joined to the negative element of the next cell, and so on throughout the series, the current passes through one cell after another, and the battery is said to be arranged *in series* (Fig. 150). Thus the difference in the potential of carbon and zinc of each cell is multiplied by the number of cells, and a battery of three cells so arranged will push its current through three times as much resistance as one cell would be able to do. The analogy of three water pumps, arranged as represented in Fig. 151, will help to make this clear. All the water which traverses the circuit must go through each pump. Each pump raises the water level by a certain amount, and it is manifest that the water pressure in the return pipe is three times as great as it would be if it returned from the outlet of the first pump.

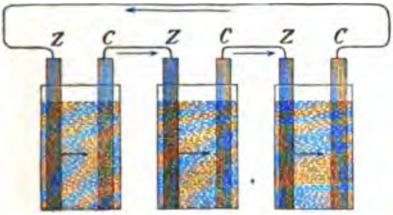

Fig. 150.—Cells in series.

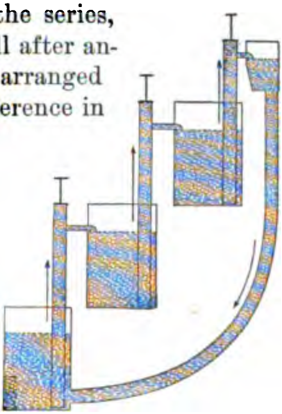

Fig. 151.—Pumps in series.

If all the positive metals are joined together and all the negative elements, the current passing through all the cells at the same moment, the battery is said to be arranged *in parallel* (Fig. 152). This is analogous to the arrangement of pumps represented in Fig. 153, where only one third of the water goes through each pump. Three pumps raise the level of the water no higher than one pump would, and the water pressure in the return pipe is no greater than it would be if one pump acted alone, but three times as great a *quantity* of water may be supplied to the return pipe as in the former case. The arrangement chosen must depend upon the work to be done, and this will be discussed in section 257.

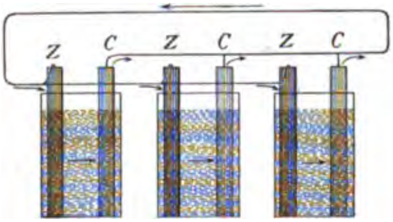

Fig. 152.—Cells in parallel.

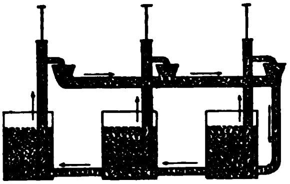

Fig. 153.—Pumps in parallel.

II. Some Effects of Electric Currents

248. **Electric Currents recognized by their Effects.**—To a casual observer there is no evidence that the cell produces an electric current, and we must therefore learn to recognize the current from some effect which it may produce. We will stop to study some of the effects of the current before we go on to consider its further production by the dynamo and thermopile. These effects cover a very wide range, and the immense variety of the phenomena growing out of electricity constitutes its chief fascination. Those which we shall consider are *physiological*, *thermal*, *chemical*, and *magnetic*.

249. **Physiological Effects.**—It is difficult to get any evidence from our sense of feeling that the cell produces any electric current, because our bodies are not sufficiently good conductors (see 234) for the cell, with its slight potential, to send any of the current through our flesh. Of course, a sufficiently large number of cells arranged in series

would send a current that might be felt, but the batteries of such number of cells as we are likely to use in the laboratory are not capable of sending through the human body any appreciable current. If the poles of two or three cells connected in series are touched to the tip of the tongue a few millimetres apart, a slight sensation is felt, but the amount of current that passes is exceedingly small. We may therefore handle our battery wires without insulation and lose no current. For more interesting physiological effects we must have high-tension currents, such as will be considered in future sections upon induction.

250. **Thermal Effects.**—Whenever a current meets resistance, heat is produced in much the same way as when mechanical motion encounters friction. In both cases there is waste of energy. Even the best conductors offer some resistance, and consequently the temperature of every conductor rises a little while an electric current is passing through it. In the case of all forms of electric light we purposely introduce resistance to the current, so as to get heat and light from it. In the arc lamp the tremendous resistance of the air produces the voltaic arc, one of our most intense sources of heat. In the incandescent lamp the high resistance of the filament of. carbon develops enough heat to make the carbon white hot.

Electric stoves are simply resistance boxes. The electric stove used in the trolley cars consists of several coils of wire. They offer so much resistance to the passage of the current that they become much heated, and then act simply as radiators. In the stoves used for cooking the wires are generally of platinum or German silver, buried in fire clay or in asbestos.

The electric furnaces used to reduce ores of aluminium and other metals consist of a fire-clay box provided at each end with a carbon terminal, and packed with a mixture of carbon and ore. When the current passes it meets such tremendous resistance that a corresponding amount of heat is developed, and the refractory ore is reduced to metal.

The current is applied with great success to the welding of metals. The pieces to be welded are pressed together with much force, and a large current is passed through the juncture. Great heat is developed and the welding is very perfect.

The solutions in the battery cells rise in temperature when the current passes, because of the resistance which they offer to the current.

If the wires from a battery of two cells connected in series be rubbed upon a file, a brilliant shower of sparks will be produced. Minute particles of metal are made incandescent by the resistance offered to the current as the wires dance along over the file.

251. **Chemical Effects.**—The chemical action in the cell produces an electric current, and this electric current is in turn able to produce chemical action. In the cell zinc decomposes the sulphuric acid, forming zinc sulphate, which remains dissolved in the water used in the cell. If, when the cell is "run down," we dip the poles of a sufficiently strong battery into this solution of zinc sulphate, the electric current will decompose this zinc sulphate again, the zinc gathering about the negative pole and the sulphuric acid gathering about the positive pole. This process of decomposing compounds by electricity is called electrolysis. When we have decomposed this zinc sulphate into zinc and sulphuric acid it will act as a battery cell and produce again an electric current. This is one form of a storage battery, and the act of decomposing its zinc sulphate into zinc and sulphuric acid by means of an electric current is called charging the battery cell, or storing electricity—an expression which is misleading.

Storage batteries, or accumulators, were first announced in practical form by Gaston Planté in 1860. In its commonest form the storage-battery cell consists of two plates of lead, each having holes filled with a paste of lead oxide, in dilute sulphuric acid. When an electric current is passed through this cell the anode (the plate of lead which is the positive pole—that is, which is connected with the wire from the negative plate in the battery) becomes covered with a coating of peroxide of lead, PbO_2, while the kathode is covered with particles of lead in a spongy form. In this condition the accumulator is said to be "charged." For this reason it is sometimes called a *storage battery*, but in reality electricity is not stored in it any more than heat is stored in coal, or houses and farms are stored in a bank. The electric current sent through the accumulator does chemical work in breaking chemical compounds, which, when they reform again, will generate a current. It is a curious fact that these chemical compounds do not reform again in the cell until the circuit is closed and the electric current produced thereby flows. Yet this is the case with every battery cell to a certain extent, and particularly so with those, such as the Leclanché type, which are called "open-circuit" cells. Storage batteries are much used for running electric launches and automobiles, and to supplement a dynamo, from which they may store energy to be expended at intervals when the dynamo is insufficient or at rest.

Electrolysis of Water.—This is conveniently carried out in the Hoffmann apparatus, shown in Fig. 154, or some other simple form like that represented in Fig. 155. The water has a little sulphuric acid added to it, in order to make it a conductor of electricity. The current from a battery of several cells is allowed to pass through the apparatus until enough gas has been collected in each tube to be examined satisfactorily. Twice as much gas collects at the negative electrode (the kathode) as at the positive electrode (the anode). The first-mentioned gas is found to burn with a pale-blue flame; it is hydrogen. The gas at the anode, when tested by a glowing splinter, is shown to be oxygen. The decomposition is expressed by the chemical reaction

$$H_2O = H_2 + O.$$

Electrolysis of Salts.—The current may be used to decompose water solutions of any of the salts of the more electro-negative metals, such as copper, nickel, silver, and gold. This is the basis of our electroplating and electrotyping. The object to be plated is made the kathode, the anode being either a plate of the metal, in which case the solution or "bath" keeps a constant strength, or else a strip of platinum (Fig. 156). The cyanides of gold and silver are generally employed, and a double sulphate of nickel and ammonia. Copper succeeds best from a slightly acid solution of the sulphate. In electrotyping, an impression of the type or cut is first made in wax or gutta-percha, and this is then rubbed over with graphite, in order to make it a conductor.

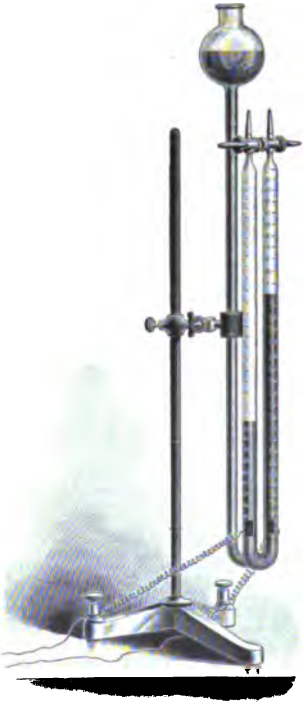

FIG. 154.—Hoffmann apparatus.

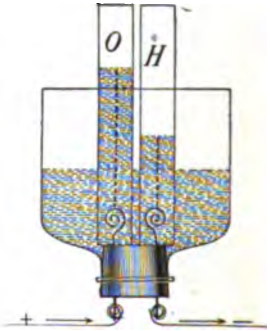

FIG. 155.—Electrolysis of water.

The mold is then suspended in a bath of copper sulphate as a kathode, the anode being a copper plate. In this way a very thin film or skin of copper is obtained, which is afterward backed with type metal and mounted on a wooden block, so as to make its face height equal to that of ordinary type.

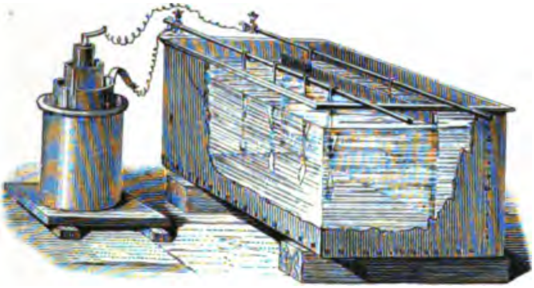

FIG. 156.—Electroplating.

Most of the copper ore of the world is bought and sold on the basis of the "electrolytic assay." About a gram of ore is digested with acid. The insoluble "gang" is filtered off. The dissolved copper is placed in a weighed platinum dish, which is then made the kathode, a little spiral of platinum dipping into the solution being the anode. The current is allowed to pass overnight. In the morning all the copper is found deposited on the platinum dish, and, after drying, may be directly weighed.

252. **Magnetic Effects.**—If the copper wire which connects the carbon and zinc terminals of a cell is made into a coil as shown in Fig. 157—which coil is called a *helix*—the electric current will develop a magnetic field. The region around this helix behaves exactly as that around all magnets.

We regard a magnetic field as an ether vortex, and to produce this we cause the electric or ether current to move in whirls. The successive turns of the wire must not touch one another, for if they did the current would take the shortest path from the carbon to the zinc. The best way to make the helix is to use wire which has a thin insulating covering. No. 24 single, cotton-covered copper wire is best. This may be coiled around a wire nail, making a helix about an inch long, with the wires, say, three layers deep. The nail may then be withdrawn, and the helix, when an electric current is passing around it, will be found to be the center of a rather strong magnetic field. The end of this helix, around which the current is passing in the direction in which the hands of a watch move, will be found to attract the north pole of a compass needle—that is, it is a south pole, and the other end of the helix is its

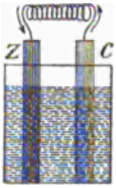

Fig. 157.—Helix.

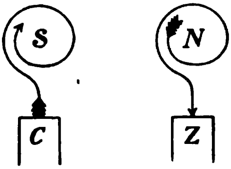

Fig. 158.

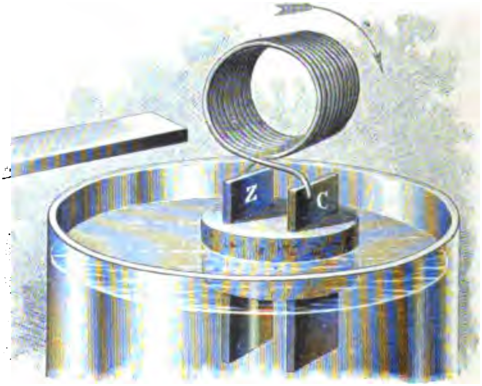

Fig. 159.—The floating helix.

north pole (see Fig. 158). Such a helix may be floated upon a battery solution, and will itself behave as a compass needle (see Fig. 159). If the wire nail is inserted in this helix it will be strongly magnetized when the current passes, and the field will be found to be much more strongly magnetic than before the iron core was used. A helix with an iron core is called an electro-magnet. We shall meet with it many times in future sections. If the iron is very soft, it will lose its magnetism as soon as the current ceases to flow. If, however, it is steel or hardened iron, it will retain its magnetism after it is removed from the helix. In this way we may make permanent magnets of steel (Fig. 160).

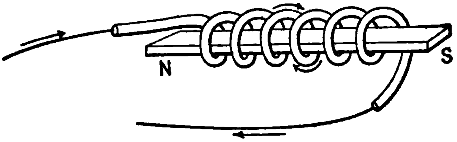

FIG. 160.

We are now prepared to state what we believe to be the connection between *magnetism*, *static electricity*, and *electric currents*. Magnetism we regard as an *ether vortex*, static electricity is an *ether stress*, and an electric current is *ether flowing in a stream*. The ether vortex is not confined to the magnet, although that is its center; the vortex extends some distance around the magnet, and is called the magnetic field. Ether stress is not confined to an electrified body, although that is the center of it. By bringing a pith ball near to an electrified body, we discover that the ether stress extends to some distance around the body.

An ether current is not confined to the conducting wire, although that is the center of the stream. We shall learn more about this in future sections.

If we bring a magnetic needle near to a straight wire through which a current is passing (Fig. 161), we have evidence that the field about the wire is affected by the electric current. The needle will be deflected toward a direction at right angles to the wire. The accompanying diagrams (Fig. 162) show the direction which the needle will take, and at the same time suggest the explanation. Suppose the current to be flowing from left to right, as represented by the large straight arrow in the upper diagram, and the needle to be brought over it, the north pole is turned toward the observer; if under it, the south pole is turned toward the observer. This permits the ether whirl to move with the ether flow. If the current flows from right to left, as represented by the large straight arrow

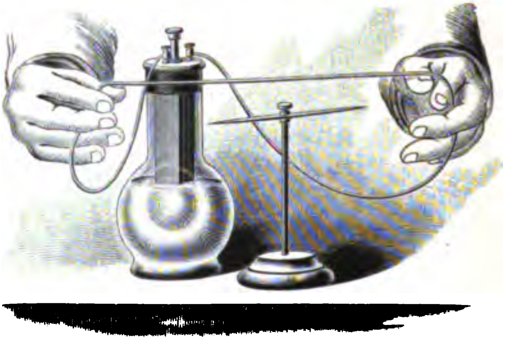

FIG. 161.

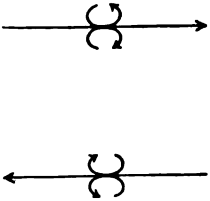

FIG. 162.

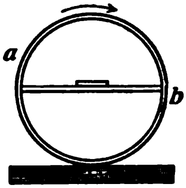

FIG. 163.

in the lower diagram, the needle will be deflected as there represented.

The galvanometer, for which we shall have much use in future sections, is presented here as an illustration of magnetism in a helix. *a b* (Fig. 163) is a coil of wire about six inches in diameter. Suspended in the center of this coil or helix is a small magnetic needle. If the electric current is sent around the coil in the direction of the arrow, a magnetic field will be created, the south pole of which is on the side of the helix toward the observer, and the magnetic needle will be deflected so that its north pole will point toward the observer.

The telegraph-sounder is a simple device for making use of the magnetic effect of the current. The diagram (Fig. 164) will make plain the principle of telegraphing.

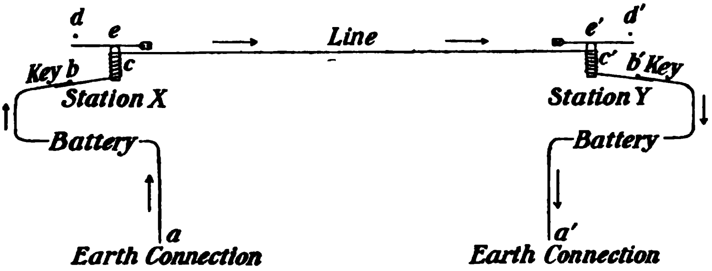

Fig. 164.—The telegraph.

Suppose the electric current to flow from the battery through the apparatus at station *X*, and through the line wire connecting this with station *Y*, and through the apparatus at *Y* and back from *a′* to *a* through the earth. The electro-magnets *c* and *c′* will attract and hold down the springs *e* and *e′*. If, now, an operator at either station wishes to signal to one at the other station, he may separate the wires at *b* or *b′*, when the magnets will cease to attract and the springs *e* and *e′* will fly up and click against the stops at *d* and *d′*. When the operator brings together again the wires at *b* or *b′*, the magnets will again pull down the springs *e* and *e′* upon themselves with a click. These clicks are made to represent letters, and thus the operators spell out words. The earth connections are made by gas or water pipes, or by metal plates buried in moist earth. The expense of a second wire is thus spared and also its resistance, since the earth offers practically no resistance. In consequence, the required battery power is reduced just one half. In reality, the earth does not act as a return wire in completing the circuit, but simply serves to keep the earth terminals at the same potential. When this is the case, the effect on the circuit is the same as if the earth terminals were in direct contact with each other.

The telegraph wires are usually strung through the air on poles, and must be supported on glass or porcelain insulators. In very large cities, however, there are ordinances against overhead wires, and the city circuits must consequently be underground.

In this case the wires are insulated, usually with gutta-percha, and are laid in pipes, opening at regular intervals into more sizable manholes. The air lines were formerly made of galvanized iron wire, but modern installations, both in Europe and America, are increasingly making use of copper wire, on account of its greater conductivity.

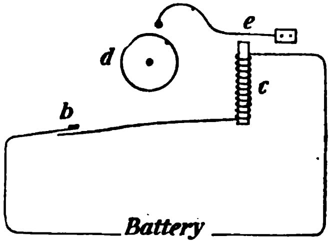

FIG. 165.—Single-stroke bell.

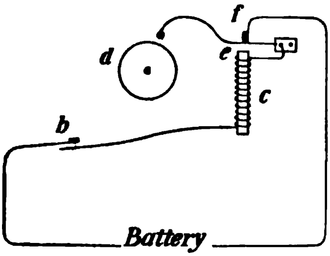

FIG. 166.—Clatter bell.

The electric bell is a further application of the electro-

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magnet. In Fig. 165, suppose we close the circuit by bringing the wires together at *b*. This may be what is called a push button or a switch. The current will cause the electro-magnet to attract the spring *e*, which is frequently called an armature. As it descends it will strike the bell *d*. This arrangement is called the "single-stroke" bell. The "clatter bell" is arranged as shown in Fig. 166. When *b* is closed the spring *e* is drawn down by the magnet, but the moment it leaves the stop at *f* the current ceases to flow, the magnet ceases to act, and the spring *e* flies upward against the stop *f*, only to be pulled away again. Thus it vibrates rapidly, and causes the bell *d* to clatter.

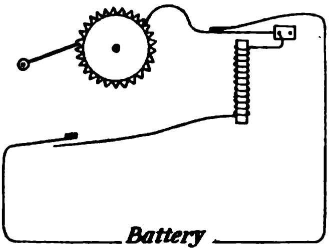

Fig. 167.—Electric motor.

The electric motor is another application of the electro-magnet. Fig. 167 shows how this electric current might be used to make a wheel go around. This device is used for many purposes, and might be called a motor; but Fig.

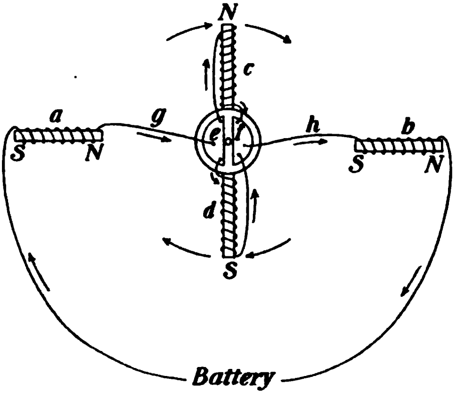

Fig. 168.—Electric motor.

168 will explain in a very general way the principle usually employed in electric motors. Suppose an electric current passes around the magnet *a*, so as to make its right-hand end a north pole. Suppose, then, the current is led by the spring to the semicircular plate of metal *e*, borne upon a wooden disk, where it divides, half of it going about the coil *c*, so as to make it an electro-magnet with its upper end a north pole, and the other half of the current going about the coil *d*, so as to make its lower end a south pole. The current then returns to the semicircular metal plate *f*, and from that by the spring *h* to the coil *b*, the left-hand end of which it makes a south pole. It is manifest that *c* will be repelled from *a* and attracted toward *b*, and that *d* will be repelled from *b* and attracted toward *a*. As *c* passes by *b* the springs *h* and *g* will change to the opposite metal plates *e* and *f*. This will reverse the current in *c* and *d*, so that while the farther end of *c* is passing through the lower half of its circular path it will be a south pole, and while the farther end of *d* is passing through the upper half of its circular path it will be a north pole. In other

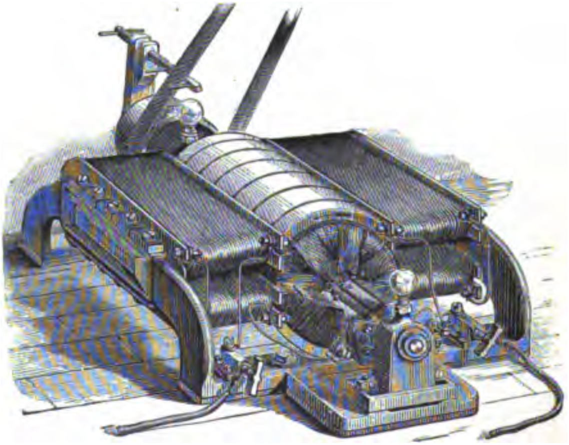

FIG. 169.—Electric motor.

words, the pole which is above will always be a north pole, and that below will always be a south pole.

The arrangement by which the current is reversed at *e* and *f* is called the commutator. These rotating magnets being fixed to an axis may cause other wheels to revolve, and thus set in motion a variety of machinery. The accompanying figure (169) is more nearly the form of motors in use. It will appear again under the head of Dynamos.

III. ELECTRICAL MEASUREMENTS

253. **The Problem of Measurement** is easy only when one has very definite ideas about what is to be measured. In the case of the electric current there are several measurable aspects. We must begin with a very definite idea of these several aspects themselves.

The thing we want to measure is manifestly *motion*, but the difficulty is that it is associated with something so altogether intangible and beyond our experience, that we are not able to call it matter, much less lay hold of it and determine its amount. Yet the best we can do is to consider the current as electricity in motion, and we must get some quantitative hold on it in order to study it at all scientifically. We must answer the question, "How much?"

The first thing that strikes us about electric motion is that it is quite independent of direction—goes up or down, right or left, north or south, wherever the conductor leads it, and apparently with equal facility. Matter does not behave in this free way, because it has weight. We can not ascribe weight, therefore, to electricity. Yet the two are alike in one respect. Matter falls to the earth, because, *for it*, that is the line of least resistance, and it is being urged on by gravitation. However little we know about electricity, we must believe that these same general principles hold, that electricity follows its own line of least resistance, and is urged on by some force quite as irresistible as gravitation.

So much happens in the neighborhood of an electric conductor, that we are coming to believe that the real current is outside the conductor, and that the conductor simply determines the *direction* of the current, pierces the ether in some way, and opens up a line of least resistance for the current to follow. In the same way we account for the force driving the electricity by assuming different electrical levels, or potential, and ascribing the driving force to difference of potential, or E. M. F. This clearly is one measurable aspect of electricity, and corresponds very closely to difference of level in the action of gravitation—as, for example, water pressure. A second measurable aspect is the resistance to the flow of the current. This may be compared to constrictions in the water pipe. The motor man when he turns on more or less current in his car does it by putting into the circuit less or more resistance, just as one may do in the case of the flow of water from a pipe opening more or less the stopcock at the faucet. A third measurable aspect of the electric current is the quantity that will flow through a conductor in a given time. This we measure by the work which it will perform.

254. **Ohm's Law.**—There are two ways of affecting the quantity of water that may flow from a water pipe: one is to change the water pressure, the other is to change the size of opening in the faucet. Just so with the measurement of electric currents. Make the pressure or potential twice as great, and we make twice as much current flow; make the resistance twice as great, and we reduce the flow of current one half. Three times as much potential, three times as much current; three times as much resistance, one third as much current, etc. This is known as *Ohm's Law*, which may be stated as follows: The current varies directly as the potential and inversely as the resistance. If we represent current by C, potential or electro-motive force by E, and resistance by R, the formula which states this law in brief form is, $C = \frac{E}{R}$.

As was stated in section 242, the unit for electro-motive force is called a *volt.* (Named in honor of Alessandro Volta, 1745–1872, born at Como, Italy.) It is very nearly the amount of pressure which is exerted by a Daniell cell (246). The unit of resistance is called the ohm. (Named in honor of Georg Simon Ohm, 1781–1854, born at Erlangen, a town of Bavaria.) It is about the resistance offered by 39 feet of No. 24 copper wire. The unit of current is called an ampère. (Named in honor of André Marie Ampère, 1775–1836, born at Lyons, France.) It is about that current which a Daniell cell will send through 39 feet of No. 24 copper wire. That is, it is the rate of flow which one volt can push through one ohm of resistance. (These units appear in the formula of Ohm's law thus: Ampères of current $= \frac{\text{Volts of potential}}{\text{Ohms of resistance}}$.) It is measurable by its chemical effects, magnetic effects, or heating effects. Let us take, for example, the chemical work which it may perform. Any current which will decompose water and liberate 0.036 grams of hydrogen in an hour is a one-ampère current. The ampère will deposit 1.18 grams of copper from copper-sulphate solution in an hour. If the solution offers ten ohms of resistance, it will require an electromotive force of ten volts to maintain a one-ampère current. If the electro-motive force is five volts, while the resistance is ten ohms, only a one-half-ampère current will flow, and it will require two hours for it to deposit 1.18 grams of the copper. If we have a ten-volt current and the resistance is five ohms, it will furnish a two-ampère current, and this will deposit 1.18 grams of copper in half an hour.

Or we may take the heating effects as a measure of the current. If an incandescent electric lamp offers a resistance of 220 ohms, a potential of 110 volts will send through it one half an ampère of current; 0.5 ampère $= \frac{110 \text{ volts}}{220 \text{ ohms}}$. Suppose this heats the filament sufficiently to make it give a light equal to that of sixteen candles—this we call a sixteen-candle-power lamp. A thirty-two-candle-power lamp will require twice the amount of current, or one ampère, and we may produce it in one of two ways: First, we may double the voltage, 1 ampère $= \frac{220 \text{ volts}}{220 \text{ ohms}}$, or we may reduce the resistance one half, 1 ampère $= \frac{110 \text{ volts}}{110 \text{ ohms}}$. But in any case the heat and light will be proportional to the amount of current which passes.

255. **The Tangent Galvanometer.**—It is our custom, however, to measure the current by its magnetic effects. It will be remembered that the galvanometer, Fig. 170, creates a magnetic field when the electric current passes around it (page 255). We have a very simple means of measuring the amount of magnetic force developed in this field, and the magnetic force is a measure of the amount of electric current which passes through the coil of the galvanometer; the needle is deflected by the magnetic force of this helix through a certain angle, and it is found that the *tangent* * of this angle

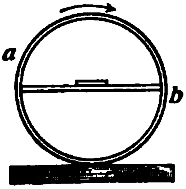

FIG. 170.—Tangent galvanometer.

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* In Fig. 171, let *a e* be a tangent to the circle; *a b* is called the tangent of the angle *a o b*, *a c*, *a d*, and *a e* are respectively the tangents of the angles; *a o c*, *a o d*, and *a o e*. The length of these tangents is given in terms of the radius of the circle. In the figure *a b* is equal to the radius; *a c*, *a d*, and *a e* are respectively two, three, and four times as great as the radius. By referring to the table of tangents, page 263, we may see that if the tangent of *a o b* is 1, the angle must be 45°; the tangent of *a o c* being two, the angle must be about 64°; likewise the angle *a o d* must be about 72°, and *a o e* about 76°. The law is that if a certain amount of current will deflect the needle from *o a* to the direction of *o b*, it will re-

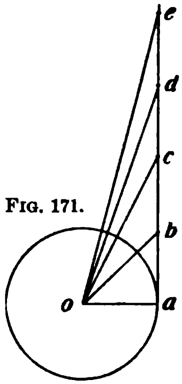

FIG. 171.

TABLE OF TANGENTS.

Deg.	Tan.	Deg.	Tan.	Deg.	Tan.
1	.02	31	.60	61	1.80
2	.04	32	.63	62	1.88
3	.05	33	.65	63	1.96
4	.07	34	.68	64	2.05
5	.09	35	.70	65	2.15
6	.11	36	.73	66	2.25
7	.12	37	.75	67	2.36
8	.14	38	.78	68	2.48
9	.16	39	.81	69	2.61
10	.18	40	.84	70	2.75
11	.19	41	.87	71	2.90
12	.21	42	.90	72	3.08
13	.23	43	.93	73	3.27
14	.25	44	.97	74	3.49
15	.27	45	1.00	75	3.73
16	.29	46	1.03	76	4.01
17	.31	47	1.07	77	4.33
18	.33	48	1.11	78	4.71
19	.34	49	1.15	79	5.15
20	.36	50	1.19	80	5.67
21	.38	51	1.24	81	6.31
22	.40	52	1.28	82	7.12
23	.42	53	1.33	83	8.14
24	.45	54	1.38	84	9.51
25	.47	55	1.43	85	11.43
26	.49	56	1.48	86	14.30
27	.51	57	1.54	87	19.08
28	.53	58	1.60	88	28.64
29	.55	59	1.66	89	57.29
30	.58	60	1.73	90	Inf.

varies as the current. For example, suppose we introduce into a battery circuit a galvanometer and a cell containing copper-sulphate solution (Fig. 172); suppose also we find that copper is being deposited at the rate of 1.18 grams per hour, and that the needle of the galvanometer is deflected to 83°. As has already been said, the amount of current which will deposit copper at that rate is called an ampère. Now, it will be found that every time an ampère of current is passed through this particular galvanometer

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quire twice that current to deflect it to the direction of *o c*, and three times that current to deflect it to the direction of *o d*, and four times that current to deflect it to the direction of *o e*.

its needle will be deflected to 83°. The tangent of 83° is 8.14 (see table, page 263). If now we send through this circuit such a current as will deposit copper at one half the above rate, we shall find that the needle of the galvanometer is deflected not to 41.5°, which would be half the angle, but to 76°, whose tangent is about half that of 83°. A current which would deposit one quarter as much copper would deflect the needle to 64°, whose tangent is one quarter that of 83°, etc. Thus a galvanometer which has been tested for some one known quantity of current may be very readily used, by aid of the table of tangents, to determine any amount of current which passes through it.

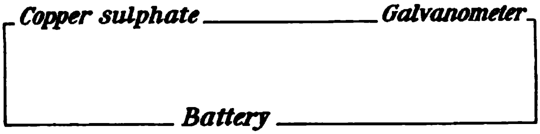


FIG. 172.

A galvanometer used for measuring the quantity of current, or the *ampères*, is frequently called an *ammeter*, but galvanometers may also be arranged for measuring the electro-motive force, in which case they are called voltmeters. Since it follows from Ohm's law that C and E depend directly upon each other, whatever measures one practically measures the other also.

Galvanometers used for voltmeters are usually constructed with a coil of very large resistance—that is, the wire is long and very fine. The resistance is sometimes as much as several thousand ohms. The amount of current flowing through such an instrument is proportional to the E. M. F., and by observing the deflections produced by known currents, we may either standardize the galvanometer by marking the voltage directly on the graduated circle, or by preparing a reference table. As strong currents would destroy such a fine coil, only tiny currents are ever sent through it. This is managed by providing two paths for the current (Fig. 173): one of low resistance, R, which will carry the major part, and the other of high resistance, r—that is, the galvanometer—to carry a very minor part. But since R and r are constant, the current through the galvanometer, though very small, will always bear a direct relation to the whole current, and serve to measure it.

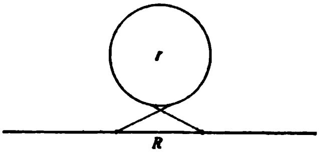


FIG. 173.

It is manifest that if we know any two of the quantities in the formula, $C = \frac{E}{R}$, we may calculate the third. It is manifest also that we must know the resistance throughout the entire circuit—that is, the internal resistance of the cell as well as the external resistance of the wires and galvanometer, and various pieces of apparatus used. We frequently designate the internal resistance by r and the external resistance by R. In which case, of course, the formula becomes $C = \frac{E}{r + R}$.

256. **Resistance** is a factor coming in at all times to reduce current strength. One method of measuring it is by means of the Wheatstone bridge. This depends upon the principle that no current will flow between two points at the same potential, and that in any given uniform conductor, the fall of potential is also uniform. Suppose $A\,B$, Fig. 174, to be a uniform conductor. In the first place, no current will flow at all if A and B are at the same potential, and a galvanometer introduced into such a circuit would show no deflection. But if A is at higher potential than B, the fall of potential in passing from A to B will be uni-

FIG. 174.

form. If the difference is three volts, any point C midway between A and B will differ from either by one and a half volt.

The Wheatstone bridge is a uniform wire stretched between two fixed binding posts, and over a graduated scale which is provided with a sliding contact, dividing the wire into two determined portions. The action can best be understood by means of a diagram, Fig. 175. The current coming from the battery E divides at A into two portions, one taking the path ADB and the other the path ACB. If a galvanometer, G, is introduced between C and D, there will be no deflection if there is no current, and there will be no current if C and D have the same potential. They will have the same potential if the resistance of AD bears the same relation to that of DB as the resistance of AC bears to that of CB, or when

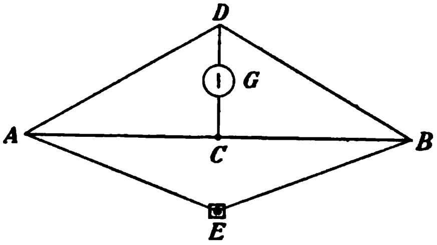


FIG. 175.—Wheatstone bridge.

$$AD:DB = AC:CB.$$

If we substitute for AD the resistance to be measured, R, and for DB some known resistance, W, we shall evidently be able to find some position for C such that no current will pass through the galvanometer. When this is the case, we have

$$R:W = AC:CB, \text{ or } R = \frac{AC}{CB} \times W.$$

Resistance Coils.—The known resistance W is usually supplied by means of a standard set of coils. They are made of German silver, with their ends soldered to solid pieces of brass on the top of the box. When all the plugs are in place, the current passes through the solid brass, and meets comparatively no resistance. When a plug is removed, the current must pass through the wire beneath, and so meet the corresponding resistance (Figs. 176, 177, and 178). A very common way to measure resistance is to place the battery, galvanometer, and object whose resistance is to be found in circuit. Note the deflection of the galvanometer needle, then put the standard resistance coils in the place of the object whose resistance is to be determined, and throw into circuit enough resistance to bring the galvanometer needle to the same point as before. The resistance, which may now be read from the standard coils, is the resistance which was sought.

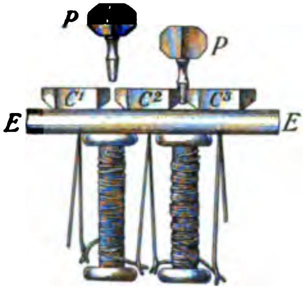


FIG. 176.

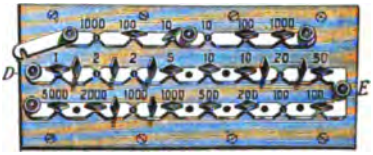


FIG. 177.

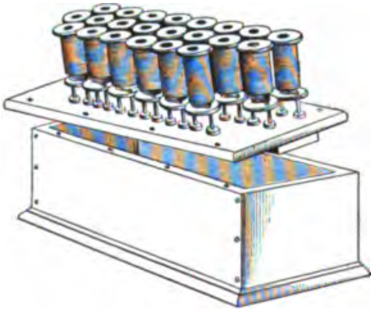


FIG. 178.

Resistance increases with the length of the conductor, and in the case of wires is greater the smaller the wire. Silver, copper, and brass, being good conductors, offer the least resistance. In general the resistance increases with the temperature in the case of metals, but decreases in the case of carbon.

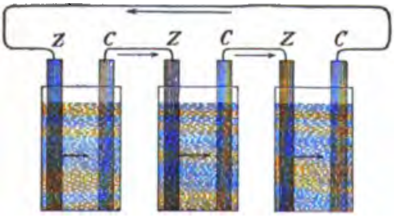
The following list shows the resistance of certain metals compared with copper, the length, thickness, and temperature being the same for all:

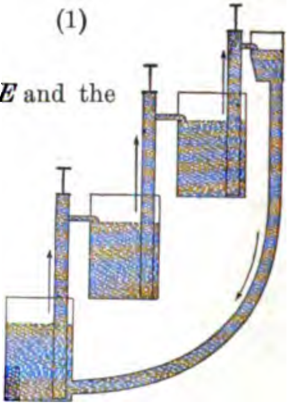
Copper	100	Iron	662
Aluminium	246	Tin	738
Zinc	446	German silver	1228
Platinum	630	Lead	1462

257. **Arrangement of Battery Cells.**—If a battery consist of n cells, and we connect them in series (247), we shall have

$$C = \frac{nE}{nr + R} \qquad (1)$$

because the potential differences E and the internal resistances r are proportional to the number of cells.





FIGS. 179 and 180.—Arrangement in series.

The same battery joined in parallel (247) would give:

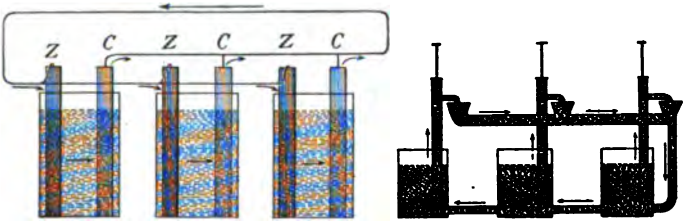
$$C = \frac{E}{\frac{r}{n} + R} \qquad (2)$$

since we really form one giant cell, whose E. M. F. is the same as a single cell, but whose internal resistance is reduced in proportion.

We reduce this last formula to the expression

$$C = \frac{nE}{r + nR} \qquad (3)$$

To give this fraction the greatest possible value, and therefore make C a maximum current, we may either increase the numerator or diminish the denominator. Comparing (1) and (3) we see that they have the same numerator, nE. The whole question turns then upon the value of the denominators. One is $nr + R$, and the other $r + nR$. If r is less than R, we can better afford to multiply r by n, and so we choose the first arrangement in series. But if r is greater than R, we can better multiply R, and we choose the arrangement in parallel.



FIGS. 181 and 182.—Arrangement in parallel.

258. **Divided Circuits.**—It often happens that a conductor divides and offers two paths to the current. This happens, indeed, every time a battery is joined in parallel. The conductor divides into as many separate paths as there are cells. In all such cases the current also divides and traverses all the paths offered. If they have equal resistance, each path gets the same amount of current, but if they have unequal resistance, each path gets an amount inversely proportional to its resistance.

The inverse of resistance, $\frac{1}{r}$, is conductance. The total conductance of the system must evidently be the sum of the separate conductances.

The circuit branching off from a main circuit is called a *shunt*.

If a current divides into two or more paths, it may be shown that the sum of the separate currents equals the main current. If, for example, in Fig. 183, the current C is divided into two currents, c' and c'', and copper-sulphate cells be introduced into the main circuit and into each of the branches, the weight of copper deposited by C will just equal the sum of the weight deposited by c_1 and c_2. The same result would have been shown by galvanometers, or any other form of ammeter or voltmeter.

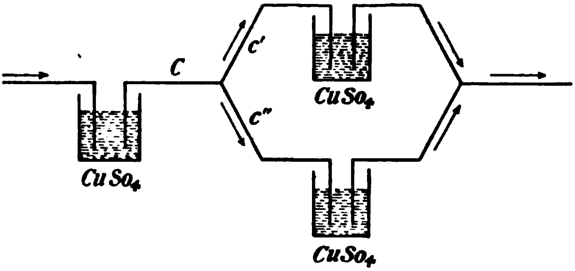


Fig. 183.—Divided circuit.

IV. INDUCTION

259. **Methods of Induction.**—Induction is applied in electricity, as well as in magnetism, to cover all action at a distance. But this means, in reality, all action confined to the surrounding medium, to the ether. Induction were better defined, therefore, as action between bodies without contact, and solely through the mechanism of the ether. Defined in this broad way, induction covers all ether stress—magnetic, electric, or gravitational.

One can not move through an ordinary apartment without more or less disturbing every particle of air in the apartment. The more rapid the movement, the greater the disturbance. A circuit of copper wire is equally sensitive to changes in the surrounding "field." No matter how brought about, the conductor responds to every change, and the induced current, like the air disturbed, is proportional to the rapidity of the change.

These changes in the electric field may be brought about by the motion of a magnet; by a field of varying strength; by the movement of a conductor through which a variable current is flowing; by the motion of the conductor itself in which the current is to be induced; or, finally, by any combination of these five variables. They can best be studied experimentally.

260. **Induction by a Magnet.**—If we take a coil of wire wrapped on a hollow spool, and connect the ends of the coil with a sensitive galvanometer, no current flows so long as the surrounding field remains the same. If, however, a bar magnet be thrust into the center of the coil, the galvanometer will show an immediate deflection. The magnet has no power except when in motion, for if allowed to remain quietly inside the coil the galvanometer needle comes to rest again and indicates no current. When the magnet

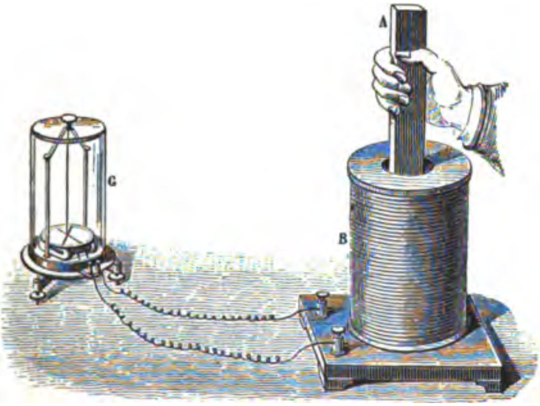


FIG. 184.—Current induced by magnet.

is withdrawn, the needle swings in the opposite direction, showing a second induced current. We find that the more rapid the motion of the magnet, the greater the deflection of the needle.

Instead of moving the magnet bodily, we may alter its intensity, and so produce the same series of induced currents. This is conveniently done by introducing an electro-magnet into the center of the coil. On making or breaking the current we get induced currents in opposite directions, surging through the coil and galvanometer; but so long as a uniform current circulates through the electro-magnet, the field remains constant and no induced current passes through the galvanometer.

We might combine these conditions and have a movable magnet of variable strength. Or we might make the conductor itself approach or recede from a fixed magnet, either constant or variable, and so induce a current in the conductor.

Whatever combination we use, the induced current depends upon the amount and rate of change in the magnetic field. Practically the current depends upon the number of lines of magnetic force cut in one second. Hence the magnet may move or the conductor may move, or both may move; or both may remain fixed bodily, and the lines themselves may move. The *relative motion* is the essential thing, and the greater the motion the stronger the induced current.

261. **Induction by Varying Currents.**—Since all currents are surrounded by magnetic whirls, we may substitute a current for the magnet in any or all of the above experiments.

Removing the iron core from the electro-magnet, the corresponding coil—which for convenience may be distinguished as the primary coil—may be thrust into the secondary coil and withdrawn, producing induced currents in opposite directions, just as in the case of the magnet (Fig. 185). If the primary coil remains within the secondary coil, and the primary current be made and broken, we shall have corresponding induced currents in the secondary coil. Similarly, if the primary coil remain fixed and the current constant, induced currents may be produced by the motion of the secondary coil. Furthermore, the parallelism between induction by currents and induction by magnets is completed by the fact that here again the strength of the induced current depends upon the amount and rate of change in the primary field.

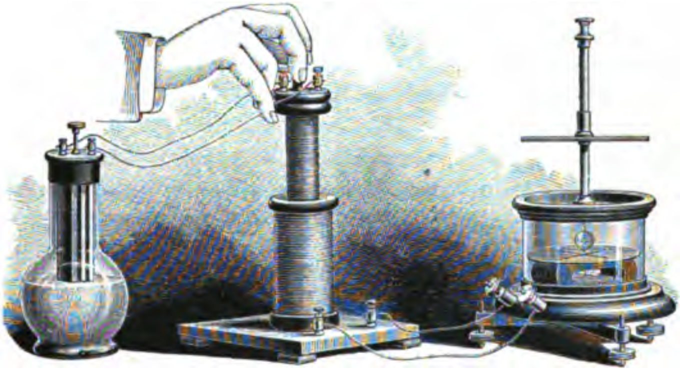


FIG. 185.—Currents induced by varying currents.

262. **Direction of Induced Currents.**—The currents in the secondary coil vary in direction according to the conditions under which they are produced. We distinguish them as *direct* and *inverse* currents. Those are direct which so flow that they would give to the magnet, were it a core of soft iron, a magnetism of the same polarity that it now possesses. Those currents are inverse which flow in an opposite direction. When the field is *increasing* in strength, the induced currents are all inverse. When the field is *diminishing,* the induced currents are direct.

263. **Strength of Induced Currents.**—Just as the direction of the induced current depends upon the conditions under which they have been generated, so, then, strength

depends upon the conditions. In a circuit of given resistance, the strength of the induced current depends solely on the electro-motive force, and this in turn depends solely upon the number of lines of magnetic force cut in one second. The voltage of an induced current is therefore increased (1) by increasing the magnetic field—that is, the number of lines; (2) by increasing the rate at which these lines are cut—that is, the speed; and (3) by increasing the length of the conductor—that is, the number of turns of wire.

264. **The Induction Coil** is a simple and effective device for producing induced currents of very high electro-motive force, by increasing the number of turns of wire in the secondary circuit. It consists of a central primary coil of short thick wire with a soft iron core, surrounded by a secondary coil of long, fine wire (Fig. 186). The primary circuit contains a current-interrupter, for rapidly making and breaking the current, and so inducing a rapid succession of inverse and direct currents. It acts upon the same principle as the interrupter used with the electric bell. (See Fig. 166, *f*.) The coil is generally mounted on a hollow wooden base, which contains a condenser made of alternate layers of tin foil and paper saturated with paraffin, and connected with the primary circuit.

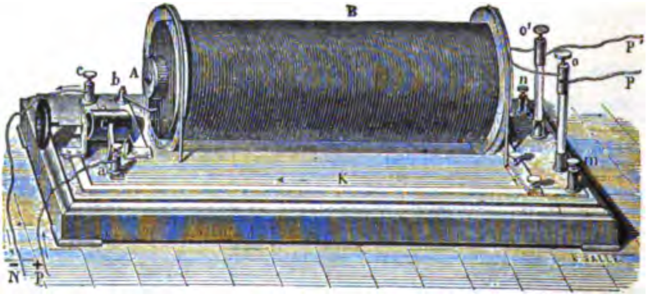


FIG. 186.—Induction coil.

The action of the condenser is to dispose of the currents which are self-induced in the primary coil on breaking the current (see next paragraph), and so avoid the spark at the interrupter. The object of having the primary coil made of stout, short wire is to reduce resistance and so increase the quantity of the primary current. The secondary coil is made tremendously long. In the case of Mr. Spottiswoode's famous coil, it is 280 miles long, and gave a spark 42 cm. long. The very large voltage of the induced current enables it to overcome the great resistance of the air, and so give us these flashes of miniature lightning.

When provided with a condenser the induction coil is known as Ruhmkorff's coil.

265. **Spark Coil and Electric Gas Lighting.**—When a current passes through a single coil of wire we have manifestly a series of parallel circuits made by the successive turns of the wire, and all the phenomena of induced currents take place in and about the single wire whenever the current itself is made or broken. On making the current, the induced current is inverse, and consequently the only effect is to retard the establishment of maximum current in the circuit. But, on breaking the current, the induced current is direct and has the effect of prolonging the flow. While this "extra current," as it is called, is most noticeable in the case of circuits containing coils, it is a self-induction, which shows itself in all circuits, and produces the spark whenever the current is broken. This principle—provided against by the condenser in the Ruhmkorff coil—is made serviceable in the spark coil, used in electric gas lighting. The core is made of a bundle of iron wires, and the coil, in this case single, consists of many turns of moderately thick wire. The introduction of such a coil into a circuit provides a good strong spark, which conveniently takes the place of a match, at any point where the circuit may be alternately made and broken. The spark which appears in a "clatter" bell (Fig. 187) at the point *f* where the current is alternately

made and broken is due to the induced current. The spark is evidence that the induced current has high voltage. This spark will light the gas. If one touches the conductor on both sides of this point, *f*, thus making it possible for this induced current to pass through his body rather than the air, he will feel a slight shock, particularly if he moistens his hands and uses metal handles to make better contact. The dry outer skin being a poor conductor, the tongue or inner surface of the mouth may be used to furnish a place for contact.

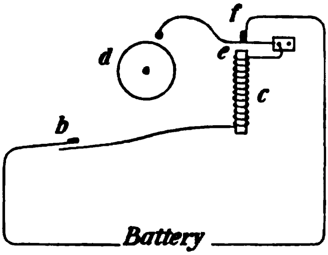


FIG. 187.

266. **The Telephone.**—Fig. 188 will serve to illustrate the essential features of the telephone. The transmitter, *T*, is a box filled with granules of carbon, into which the battery wires enter. *P* is the primary circuit of an induction coil. Tapping upon the box, *T*, or speaking into its causes the battery current to vary in strength. These variations in the primary circuit cause a secondary current of high intensity to surge to and flow through the secondary coils, *S* and *S′*, and around the permanent steel magnets, *m* and *m′*. When these induced currents go in one direction they strengthen the magnet, and when they go in the opposite direction they weaken the power of the magnet.

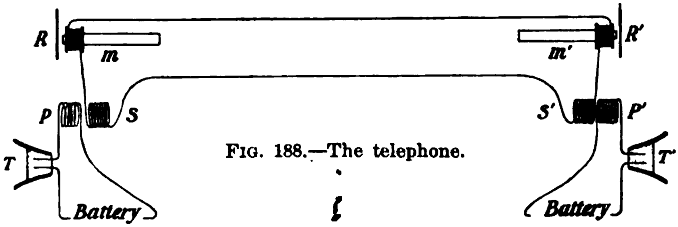


FIG. 188.—The telephone.

This causes the disks of soft iron, R and R', to vibrate exactly as they would if one spoke directly against them, and, strange to say, if one of these receivers, R or R', is held near to a person's ear, this vibration will reproduce the sounds which are made by a voice speaking into the box of the transmitter, T or T'.

267. **Transformers.**—If the electric current is to be conducted far, as, for example, to light dwellings several miles away from the central station where the electricity is produced, it must have high voltage to push its way through the long conductors. The voltage will probably need to be so high as to be a deadly current. Before receiving this into our houses, we would prefer to have its voltage reduced. This is done by transformers which are simply induction coils. What we lose in voltage in this way we gain in quantity, as might be expected from what we know of the conservation of energy. Transformers of the induction coil type require alternating currents. They consist of an iron core, a primary coil, and a secondary coil. The ratio of the electro-motive force in the primary coil to that in the secondary coil is known as the *ratio of transformation.* This may be either up or down—that is, the voltage may be either raised or lowered. As this depends upon the number of turns of wire in the two coils, the ratio of transformation is practically the ratio of the number of turns of wire in the primary coil to the number of turns in the secondary coil. If, for example, an external circuit has a pressure of 3,000 volts, and we wish a house current for incandescent lamps under a pressure of but 100 volts, the ratio will clearly be 30 and the coils will be wound accordingly. In a closely peopled district the transformer may be at the entrance to the town, while in a more scattered district the transformer may be in each house.

V. ELECTRIC CURRENTS BY MECHANICAL MEANS

268. **The Magneto-Electric Machine.**—Faraday followed up his discovery of current induction in 1831 by the invention of a magneto-electric machine. It consisted of a copper disk mounted to rotate between the poles of a permanent horseshoe magnet. The current generated in the disk was collected by strips of copper pressing respectively against the axle and the circumference of the disk. This little machine is the honorable ancestor of all the company of machines, great and small, magnetos and dynamos, that have since been invented for the purpose of turning mechanical motion into electric energy. It is the simplest combination possible of the two essential elements, a magnetic field and a movable conductor.

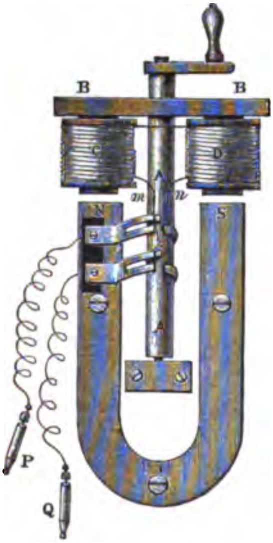


FIG. 189.—Magneto-electric machine.

Later machines substitute a coil of wire, an "armature" for the disk. A simple form of this is presented in Fig. 189. It is manifest that the current is produced in this machine by causing a helix of wire to alternately approach and recede from a steel magnet. The current thus induced has high potential. It is used by physicians in treating patients by electricity. Its more common use is for telephone calls.

269. **The Dynamo.**—It was early realized that no field magnet of steel could be so powerful as an electro-magnet. In the dynamo this field electro-magnet is energized by means of the current generated by the machine itself. This is possible by reason of the residual magnetism which

is found to inhere in the iron core of the field magnet. The field thus produced is very weak, but it is not without effect. When the armature rotates in this field, very feeble currents are set up. These pass into the external circuit and through the coils of the electro-magnets, thus strengthening the magnetic field, which in turn induces stronger currents in the armature. By this cumulative process the field soon mounts to its maximum strength, and the machine generates a powerful current.

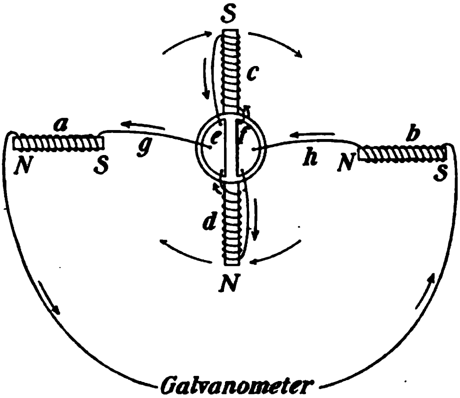


FIG. 190.—The dynamo.

The principle of the dynamo may be illustrated by Fig. 190, which will be recognized as very closely resembling Fig. 168, used to illustrate an electric motor. A galvanometer has been substituted for the battery, to indicate the current which this will produce. The electro-magnets *a* and *b* are the field magnets, and the electro-magnets *c* and *d* are the armatures. The iron cores of these electro-magnets are never entirely without magnetism, hence if we cause *c* and *d* to rotate, when they approach *b* and *a* they will induce ***reverse*** currents in the wires which encircle these cores, and when they recede from *b* and *a* they will induce ***direct*** currents in these wires. This would result in an alternating current if it were not for the commutator (see pp. 259 and 281).

All dynamos consist essentially of three elements:

1. The magnetic field.
2. The armature.
3. The collecting apparatus.

a. Commutator in the direct-current machines.

b. Collecting brushes in the alternating-current machines.

The Magnetic Field.—The smaller dynamos have a simple field produced by two pole pieces of opposite polarity, facing each other. Each pole piece is hollowed out into a semi-cylinder, and as the two pieces almost touch each other, the armature rotates in a nearly closed cylinder of highly magnetized iron (Fig. 191).

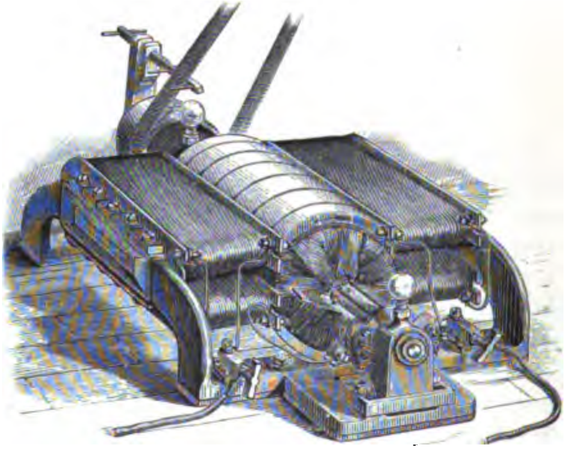


FIG. 191.—The dynamo.

The powerful modern dynamos are frequently multipolar, having four, six, or even eight pole pieces.

The armature in all modern machines is made up of many circuits. The single-coil armature can not give a steady current, because at each reversal of current—that is, twice every rotation—the current must be reduced to zero, and consequently the current in the external circuit is in reality a series of momentary currents, all in the same direction but not continuous. By having several separate circuits moving in different parts of the field, we shall always have one or more of them current-producing, and consequently in the external circuit, though the current is still subject to pulsations, it never entirely dies away. It is also possible to cut out the separate circuits when they are not active, and so reduce the resistance of the armature.

The Collecting Apparatus—The Commutator.—When the current desired must be direct, the collecting brushes have the added function of changing the alternate currents into a direct and continuous one. The simple commutator has already been described in connection with the electric motor (page 259).

By referring to Fig. 190, we may see how these brushes serve to change an alternating current into a direct one. Suppose *c* and *d* to be approaching *b* and *a* respectively. Currents will be induced in the wire encircling these cores which will take the direction of the arrows—that is, a current will be induced which will pass around *c* from *f* to *e* and around *d* from *f* to *e*. These currents will combine and pass out by the spring or "brush," *g*, around the core *a* so as to intensify its magnetism, through the galvanometer, whose needle it will deflect, showing at the same time the direction and the strength of the current, then around *b* so as to increase its magnetism, and finally back to *f* by the spring or "brush," *h*. When *c* and *d* pass *b* and *a* and begin to recede from them, the current which encircles them will be induced in the opposite direction, but at the same instant the brushes shift to the opposite plates, *e* coming under *h* and *f* coming under *g*. So that the moment the magnets *c* and *d* require the current to pass from *e* to *f*, *e* comes in contact with *h* and *f* with *g*, and thus the current continues to flow from *h* to *g* as before. Of course, it is understood that *e* and *f* are semicircles of metal upon a wooden disk, so that the only way the current may pass from *f* to *e* is through the wires which encircle the cores *c* and *d*.

In the case of alternate-current machines, the brushes have only to collect the current and send it over the main circuit. *Alternators* are very much used in electric lighting. The current surges back and forth so rapidly through the lamp as to produce a steady light. They have the advantage of requiring no commutator. The Westinghouse machine is the one best known in America.

The total output of electric energy in any machine is equal to the product of C and E or C E Watts, and this divided by 746 will give the equivalence in horse power. The mechanical efficiency is the ratio of the total output of energy to the energy put into the dynamo in the form of mechanical work. It must be remembered that we never get out of any machine as much as we put into it. We use a steam engine or water power to cause the dynamos to go; a 60-horse-power steam engine can not produce electrical energy through the dynamos which will do the work of 60 horse power. Electricity is not to be regarded as a source of power. It can not be called a rival of steam, since we are dependent upon steam to produce it. Its use is to transmit the power of the steam engine, and hence, if it is the rival of anything, it is the rival of the engine belt. A short time ago most of the street cars in New York city were cable cars—that is, they ran by grappling a cable, or huge engine belt, which ran from a central steam engine for many miles in a conduit under the street. This cable was not the source of power; it only transmitted the power. But more recently electricity has been adopted as a successful rival to this cable as a means of transmitting the power of the central steam engine. The engine is still the power which moves the cars, but instead of pulling them along now by means of a very long cable passing around the driving wheel of the engine and for miles under the street, the engine now operates dynamos, and the dynamos send the current through conductors running in conduits under the street where the cable used to run. The cars receive the electric current from these conductors through motors underneath each car, which are geared to the car axle. Whenever the motorman turns the electric current upon a car to make it go, it throws a load upon the central steam engine just as much as the cable did; and when the electric car goes up hill it throws an extra load upon the engine, just as the cable did; and when the electric lights or the electric radiators in the cars are turned on, the central engine does a definite additional amount of work, which requires a definite additional amount of coal to be burned just as truly as though the cars were heated by steam or lighted by coal gas. If the dynamo current is used to ring an electric bell, or decompose water, or do work of any kind, the dynamo goes harder and the steam engine goes harder. More steam must be produced and more coal burned to just the extent of the work performed.

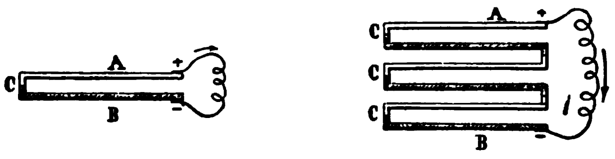
Electricity is the most convenient method of transmitting power. It will go over hill, through dale, up and down, right and left, and may be tapped wherever you will. It has now become the most economical method as well. The more carefully the current is studied, the more wisely are we able to make use of it. In any circuit the loss of energy appears as heat. By sending currents of excessively high voltage, as much as 10,000 volts or more, with current strength of only a few ampères, this loss is made comparatively trifling. When the current has reached the place where it is to be used, its character may be changed, as desired, from alternating to direct, and from high voltage to low voltage, with proportionally increased quantity.

As time passes, the water powers of the country are being increasingly harnessed to the work of current generation, and the current is being transmitted over long distances. At the Frankfort Electrical Exhibition a current of 140 horse power was brought 117 miles from the Falls of the Neckar with a loss of only 26 per cent. It is also quite possible that we may speedily find it more economical to burn our coal at the mines themselves, and send the energy to town over copper wires instead of in railroad cars.

The usefulness of the current depends very largely upon the fact that it may readily be transformed into mechanical motion again by means of the *electric motor.* In the dynamo we put in mechanical energy and get out electric current; in the motor we put in current and get out mechanical motion. Dynamo and motor are thus the converse of each other. They are, indeed, entirely interchangeable. A dynamo fed with current becomes a motor; a motor fed with mechanical motion becomes a dynamo.

VI. ELECTRIC CURRENTS PRODUCED BY HEAT

270. Thermo-electric Currents.—When the junction of two dissimilar metals, such as antimony and bismuth, is heated and their colder ends are connected by a copper wire, a current is found to flow in the wire from the antimony to the bismuth. When several such pairs are united in series, and the alternate junctions heated, the resulting thermo-electric current is proportional to the number of pairs (Figs. 192 and 193).



FIGS. 192 and 193.

271. **The Thermopile** is a compact bundle of such antimony-bismuth pairs, sometimes in great numbers, and when connected with a sensitive galvanometer forms a wonderfully delicate means of detecting and measuring the slightest differences of temperature. It is with this instrument that we explore the spectrum and measure the comparative temperature of the various rays. Thermopiles are now manufactured and sold, which are a very practical means of furnishing electric currents for laboratory and lecture-room work.

LIGHT

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CHAPTER XXVI *

RAYS OF LIGHT IN STRAIGHT LINES

272. **What is Light?**—We know that sunlight tans the skin and fades the colors in our clothes, while at the same time it causes the brilliant colors of the flowers. It makes the green color in plants, for potatoes sprout and grow white vines in a dark cellar, but green ones in the open sunlight. It assists the healthy growth of most plants and animals, but hinders the growth of molds and many obnoxious germs. Milk pans, butter pots, bread jars, bedding, etc., are put out to "sun" in order that they may become "sweet." Sunlight is the most efficient disinfectant for our apartments. Yet, what is this light? We speak of its coming from an object and going to an object, and we know that it requires about eight minutes for light to travel from the sun to the earth, about forty minutes for it to come from the planet Jupiter, about four hours for it to come from the planet Neptune, and about forty years for it to come from the North Star. Thus the velocity of light is 186,000 miles per second. This is also the velocity of electricity and of heat radiation. What do we mean when we speak of light streaming into a room? Is it a substance? Has it weight? Can it fill a space and exclude other things from the same space? We naturally think of light as closely connected with heat. We are

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* Considerable portions of these chapters on Light have been taken from Woodhull's First Course in Science, with the permission of the publishers, Messrs, Henry Holt & Co., New York.

familiar with the heating of substances until they give out light, first dull red, and afterward brilliant white light. We naturally think of both light and heat as being the essential characteristics of the sun's rays. In succeeding pages we shall learn how to concentrate the sun's rays by means of concave mirrors or convex lenses, so as to set fire to wood or paper. We shall also learn how, by means of prisms, to separate the light rays from the heat rays. They may be separated also by filtration or absorption, as has already been stated in sections 202 and 203. From this we may learn that while heat rays and light rays are very closely associated, they are not the same. Our present conception is that light rays, heat rays, and electric currents are all forms of ether vibrations, differing only in wave lengths. Those which are capable of exciting the optic nerve we call light rays; they have the shortest wave lengths. Those which excite the nerves of temperature sensation we call heat rays; they have medium wave lengths. Those which produce electric phenomena we call electric waves; they are the longest of the three kinds mentioned here. These waves may readily be transformed, the one into the other, and all may set up those molecular motions in matter which we call heat. The distinction between these various kinds of ether vibrations will be made more clear in section 331.

273. **How the Velocity of Light was determined.**—It was noticed by a Danish astronomer, Olaf Roemer, in 1675, that the observed and computed times of the eclipse of Jupiter's satellites differed by an amount too great and too constant to be assigned to observational error. The eclipse of a satellite occurs, as we all know, when it passes into the shadow of its planet, and the precise time and duration of an eclipse may therefore be calculated with great accuracy. Roemer noticed that when the eclipse was seen while the earth (Fig. 194, *A*) and Jupiter were on the same side of the sun—as the astronomers say, "in conjunction"—the

time was 16′ 36″ earlier than when the earth (Fig. 194, *B*) and Jupiter were on opposite sides of the sun; that is, "in opposition." In the latter case it is very plain that the light reflected from the satellite has to travel farther through space by just the diameter of the earth's orbit—about 184,000,000 miles. Dividing the distance by the time in seconds, we have a speed of about 186,000 miles per second. Several more refined methods of determining the velocity of light have been employed, but all give about the same result.

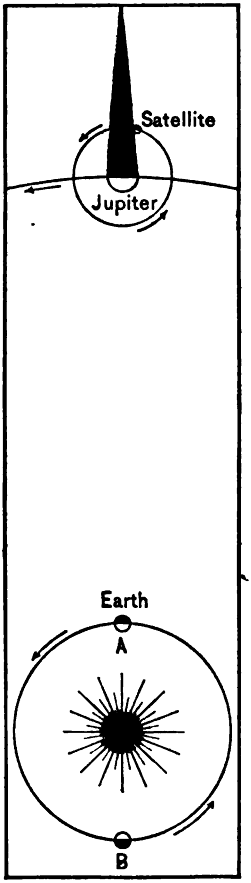

FIG. 194.—The velocity of light.

274. **Some Results of the Fact that it takes Light Time to travel.**—As a result of the appreciable time required by light to pass over space, we see the celestial universe never as it *is*, but always as it *was*. Even the moon, our nearest neighbor in space, is over a second behindhand in all her reports, and the sun is 8′ 18″ behind time. He is mathematically above our horizon by that amount of time before we see him at all, and he remains visible to us for the same length of time after he has really passed below the western horizon. Now in eight minutes of time the earth will cover an angle of 2° in rotation. But the sun, as seen from the earth, only covers an angle of about half a degree. Consequently the sun is really four times his own diameter above the horizon before we know that he is up at all. (These calculations neglect refraction, Chapter

XXIX, section 306.) The reports from the distant planets are correspondingly retarded, but the delay is the most noticeable in the case of the fixed stars. The nearest one, *α* Centauri, is so far off that it takes about three and a half years for its light to reach us. Sirius, the brightest star in our heavens, requires 16.7 years to send its light to us; Arcturus 25.4 years; Polaris, the North Star, 42.4 years; and *σ* Draconis 129.1 years—that is, if the last-mentioned star should cease to send forth light to-day, it would be 129.1 years before its last light wave would reach us, although during each second in all that time it would have traveled toward us at the inconceivable speed of 186,000 miles.

275. **The Sources of Light** are practically the same as the sources of heat—the sun, chemical energy, mechanical power, and electricity. These agents all have the power of setting up ether vibrations of such rapidity that they are sensible to us as light. The one principle in all our artificial lights is the heating of matter to incandescence—that is, to such a temperature as will set the ether into vibration within the prescribed limits of light. In the case of candle, kerosene lamp, or gas flame, by far the largest product of the chemical action is heat. This heat raises a small portion of the more refractory particles of carbon to incandescence, and these are responsible for all the light. This is well illustrated by holding a small wire in the flame of a Bunsen burner until it gets white hot. To gain the incandescence needed a high degree of heat is required. We are obliged to spend much of our energy in producing the long vibrations in the ether that are of no direct use in illumination. It is very natural, therefore, that physicists should look to the possibility of producing the shorter ether waves, which affect our eyes as light without passing through the heat stage at all. Tesla especially has worked over this problem with much patience and ingenuity.

276. Photometry—Law of Inverse Squares.—The farther we get away from a light the less intense it becomes. Let a candle flame (Fig. 195) be the source of light. We can picture rays going out in all directions. Suppose we trace the four rays which at any given distance, say one metre, bound a one-inch-square screen. As the rays come from a common center they are divergent, and the farther away we go, the wider apart do they become. At a distance of two metres let us place a second screen. By similar triangles each side of this second square must be twice as long as those of the first, and consequently the area must be four times as great as that of the first. If we remove the first screen, the amount of light that formerly fell on it is now distributed over four times the area, and consequently can be only one fourth as intense. If we place a third screen three metres away from the flame, each side of the square will evidently be three times as long as those of the first, and the area consequently nine times that of the first. If the second screen be now removed the original illumination is spread over nine times the area, and consequently can be only one ninth as intense. The distances are, 1 : 2 : 3; the areas, 1 : 4 : 9; the intensities, $1 : \frac{1}{4} : \frac{1}{9}$. Hence the law of inverse squares: *The intensity of light varies inversely as the square of the distance from the source.* The law holds for gravitation, heat, and the attractions and repulsions of magnets and electrified bodies. In every case the force varies inversely as the square of the distance. The standard in America and Great Britain is the candle power. A standard sperm candle, weighing six to the pound, seven eighths inch in diameter, and burning 120 grains an hour, gives 1 candle power; an average gas jet

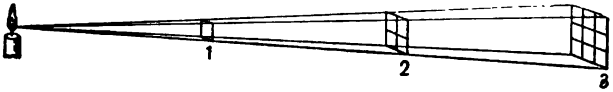

FIG. 195.—Law of inverse squares.

yields 10 candle power; an incandescent lamp usually 16 candle power; the more powerful oil lamps as high as 60 candle power; and the usual arc lamps about 1,200 candle power.

Photometry is a science of light measurement. It has both scientific and practical importance. Since light, like other commodities, is now bought and sold, people want to know how much they are getting or giving. An instrument for measuring the intensity of light is known as a *photometer*. We will consider only one. All methods of measuring light depend on the law of inverse squares.

Rumford's Photometer.—If a vertical rod or other opaque object be placed in front of a screen (Fig. 196), and light from two sources fall upon the rod, it will cast two shadows on the screen. Each shadow, however, will be illuminated by light coming from the other source. By having the shadows not too far apart, we may compare their intensities by the eye with fair accuracy. If the lights are placed at suitable distances, the shadows may be made equally intense.

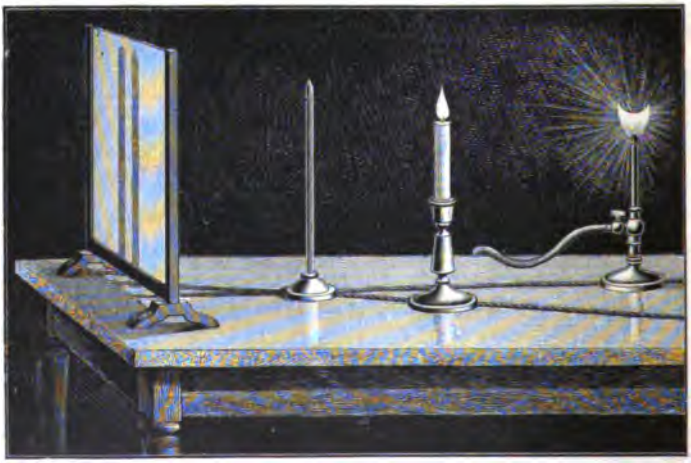

FIG. 196.—Photometer.

As the illumination from both sources is now equal, their candle powers will be as the square of their distances from the screen.

277. **The Relative Illumination of a Page of Reading Matter when held near to or far from the Source of Light.**—A kerosene lamp or a gas flame may give a light of sixteen candle power, and when we reflect that not many years ago people used fewer candles than we now use of lamps or gas jets, it appears that we are more than sixteen times as well provided with light as our ancestors. They, however, usually held a candle very near to the page while reading, and people in these days often employ a poor lamp and sit far from it. One should frequently remind himself that when he is twice as far from the light he receives one quarter as much of it, and when he is three times as far away he receives only one ninth as much of it, etc.

278. **Relation between Temperature and Intensity of Light.**—It is found that the intensity of the light proceeding from any given source increases remarkably with an increase in the temperature of the source. Authorities differ as to the temperature at which light waves begin to be given off, Weber placing it at 390° C. and Draper at 500° C. It depends, of course, upon the sensitiveness of the observer, and we can never know absolutely. Ordinary solids must be heated from 800° C. to 1,000° C. in order to emit rays of white light—that is, to become white hot. But all observers agree as to the remarkable increase at the higher temperatures. It is estimated that platinum gives thirty-six times as much light at 1,400° C. as it does at 1,000°. This fact is utilized in the incandescent electric lamp. The carbon filaments are heated just as hot as they may be without suffering too rapid disintegration. Economy is found in the nice balance between these two considerations. The temperature of the "crater" of an arc lamp is about 3,500° C. Hence its large illuminating power and its economy.

279. The Visual Angle: How we use it for estimating Distances.—The angle which the lines of light from the opposite extremities of an object make at the eye is called the visual angle. Our estimates of the size of things seem to be founded to a certain extent upon their supposed distance and the visual angle which they subtend. This marvelous faculty which we have of judging distance is undoubtedly acquired by a slow process of education. The story is familiar of the person born blind who, having in later years obtained his sight through a surgical operation, reached out his hand to lay it upon a distant church steeple which he supposed to be near enough to touch. Subtending so small a visual angle as it did, if he conceived its distance so little, he must have thought it a miniature toy. One appreciates that this faculty can be trained when he sees how efficient sailors become in the use of it. The landsman finds himself greatly at loss to estimate distances upon the sea.

If we can form no conception of the distance of an object, we are at a loss to make any estimate as to its size. People sometimes amuse themselves making comparisons between the apparent size of the moon and that of familiar objects. One says it looks about the size of a silver dime, another compares it to a silver dollar, and still a third finds a carriage wheel represents it. How completely without foundation these estimates are will be seen when one considers that if the eye were placed at one end of a metre stick, and an object one centimetre in diameter were placed at the other end, it would subtend about the same visual angle as the moon.

Some curious errors of judgment as to size occur when we have formed a wrong estimate of the distance of an object. In the dim twilight, one evening, a cat shot across the field of vision and ran up a little tree not more than four rods distant from the observer, who had not noticed the little tree because a very large tree about twice as far distant stood directly in line with it. Supposing, therefore, that the cat was twice her actual distance away, he was at the moment rather appalled at the apparition of a cat three feet long instead of eighteen inches, as she probably was. Such hallucinations are apt to fade from the mind as suddenly as they come.

The sun and moon each subtend a visual angle of about half a degree. The sun is about four hundred times as far away as the moon, and is about four hundred times as broad. Yet they appear to us to be about the same size, because we conceive of them as being at the same distance. If by any means we could make the sun appear to be farther from us than the moon, it would appear larger. To most persons the sky appears like a flattened dome, with the zenith much nearer than either horizon. Hence the sun and moon appear to us larger when in the horizon than in the zenith.

The sun is so far away that the rays of its light which reach us are very nearly parallel. The greatest possible variation from parallel would obviously exist between those rays which start from opposite extremities of the sun's disk and meet at the eye of the observer. Such rays would vary half a degree from parallel.

An object becomes invisible when it subtends a smaller angle than $\frac{1}{300}$ of a degree. If it is one of the largest bodies in the universe, but far enough distant to subtend $\frac{1}{300}$ of a degree, it is invisible without the aid of a telescope; or if it is ever so near at hand but subtends so small an angle, it is invisible without the aid of a microscope. These instruments increase the visual angle by means of lenses, as will be explained in Chapter XXIX.

We are deceived with reference to the size of an object if it gives a very brilliant light. The filament in an incandescent electric lamp, which is so small as to be seen with difficulty when it is not giving light, appears very much larger when it is giving light. The sun, although it subtends the same visual angle as the moon, appears larger because it is more brilliant. When the sun is seen through a thin cloud which shuts off some of its light, persons are often surprised to find that it appears smaller than they had imagined.

280. **Shadows.**—In Fig. 197 let *L* represent a point of light, *c d* an opaque object, and *e f* a screen. It is manifest that no light from *L* will pass into the region *c d e f*. This is the shadow. Its length may extend indefinitely as the screen is moved away from *c d*. We more often think of the shadow as being merely that portion of the screen which receives no light.

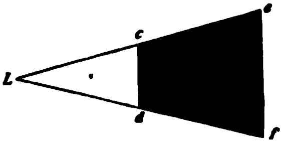

FIG. 197.—Umbra.

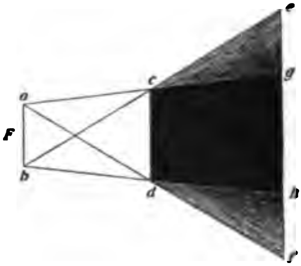

FIG. 198.—Umbra and penumbra.

Umbra and Penumbra.—In Fig. 198 let *F* represent a flame, and let *a* and *b* represent its extremities; *c d* is an opaque object, and *e f* a screen as before. The region into which no light may pass is *c d g h*. Around this there is a region *c e g* and *d f h* into which a more or less limited portion of the light from *F* may pass. To distinguish between these regions, we call the portion which receives no light the umbra, and the other the penumbra. The penumbra grows gradually denser as we pass from its outer limits inward toward the umbra, and there is no distinct dividing line, as *c g* or *d h*.

281. **The Moon's Shadow—Eclipses of the Sun and Moon.**—In Fig. 199 the angle *a o b* is made just half a degree. If an observer were stationed at *o*, and the lines *o a* and *o b* were extended 240,000 miles (the distance of the

moon), they would then be just far enough apart to span the moon—that is, 2,000 miles apart. If then they should be extended 92,500,000 miles (the distance of the sun), they would be far enough apart to span the sun—that is, 860,000 miles apart.

If it were strictly true that both the sun and moon subtend an angle of half a degree, it would follow that the moon's shadow as cast by the sun would be just long enough to reach the earth. The truth is that the moon's umbra is sometimes a little longer than its distance from the earth, and it covers a small portion of the earth's surface when it chances to sweep across it. Usually, however, we pass through nothing but the penumbra on an occasion of an eclipse of the sun.

The umbra has the shape of a cone, whose length is about 240,000 miles and whose base is about 2,000 miles. The penumbra is also an exceedingly slim cone, whose base is removed to an indefinite distance, and whose apex is cut by the umbra, which extends into it like the crater of a volcano. Fig. 200 gives a suggestion of their appearance.

The earth's shadow is similar in appearance to the moon's. The umbra is a cone whose base is about 8,000 miles in diameter, and whose length is about 868,000 miles.

It is convenient to remember that the length of the earth's umbra is about equal to the diameter of the sun, but it is more to our present purpose to notice that it is nearly four times as long as the moon's umbra, and herein lies the reason for its darkening the face of the moon more often than the moon's shadow eclipses the earth. In Fig. 200 sunlight is supposed to come from the left-hand margin of the page in lines deviating from parallel, as Fig. 199 represents, and lighting half of the earth

Fig. 199.—Relative proportions of moon's shadow.

and moon. The umbra cast by each, with its proportional length, is shown. The penumbra in each case may be imagined. The moon is represented as approaching the part of its orbit where it will cast its shadow upon the earth. Persons upon the earth's surface will, where the shadow passes, notice a dark body apparently passing across the face of the sun. This phenomenon is called an eclipse of the sun. It requires about a month for the moon to revolve around the earth; hence in about half a month it will be approaching the earth's shadow, and when it passes through it, persons upon that part of the earth's surface turned toward the moon will notice a dark body apparently passing across the face of the moon. This phenomenon is called an eclipse of the moon. From this it would appear that there should be an eclipse of both sun and moon each month, but this is certainly not the case, an eclipse of the sun being very rare, and one of the moon occurring far from once a month. This is explained by the fact that the moon does not revolve in the same plane as that in which the earth's shadow lies, as will be seen by referring to Fig. 201, which represents what we might suppose we would see if we were to look down upon Fig. 200 from the direction of the top of the page. From this it would appear that an eclipse of neither sun nor moon might ever occur. But it

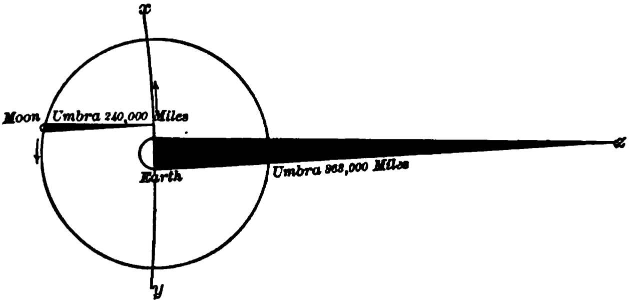

FIG. 200.

must be remembered that the earth accompanied by the moon is revolving around the sun in the plane in which *x*, *y*, and *z* lie in Figs. 200 and 201, and there will be places in its orbit where eclipses may occur—eclipses of the moon far more frequently than eclipses of the sun, because the earth's shadow is so much larger than the moon's. It must be true that whenever any place comes within the umbra, a total eclipse occurs for that place; hence we see why partial eclipses are tolerably frequent, while total eclipses are very rare. It should be mentioned that the orbit of the earth is slightly elliptical, and therefore the sun is a little nearer at one time than another, and the umbra of both the earth and the moon must therefore be a little shorter at one time than another. For this cause the umbra of the moon is not long enough to reach the earth during a portion of each year.

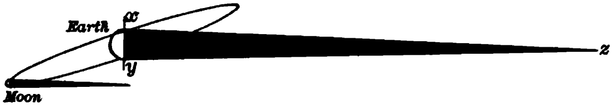

Fig. 201.

It may be interesting to note that two rays of light starting from opposite edges of the sun, and meeting at a point on the earth's surface, converge at the rate of 1 mile in 114; but if they extend from opposite edges of the sun to opposite edges of the earth, they converge at the rate of 1 mile in 108. Of so little importance is the earth's diameter when considering the vast distances between the heavenly bodies, that the earth may be looked upon as a mere point in space. A young child looking at the moon over his head thinks he may walk out from under it, and it is many years before he really appreciates that on account of the moon's great distance from the earth, it may appear to be overhead at the same moment to two persons situated many miles apart.

282. Light through Small Apertures.—In Fig. 202, *c d* represents a very small hole, about one tenth of an inch, in a piece of cardboard an inch or two in front of a candle flame, and a screen is held a few inches behind it. An inverted image of the flame will appear upon the screen. The reason for the image being inverted and for its being more or less indistinct will be seen from a study of the figure. Light from the tip of the flame *a* will fall upon the screen at *a'* and will cover an area somewhat larger than the hole *c d*. Likewise a point, *b*, at the base of the flame, will illuminate that portion of the screen marked *b'*. The light which comes from the single point *b* not only spreads over an area considerably larger than the hole *c d*, but it is also overlapped by the light from neighboring points in the flame. Hence the image is more or less indistinct. When a pencil, or similar object, is passed downward between the flame and *c d*, the shadow of the pencil moves upward upon the screen, and *vice versa*; also when the pencil is moved horizontally in a direction parallel to the screen its shadow makes the reverse movement.

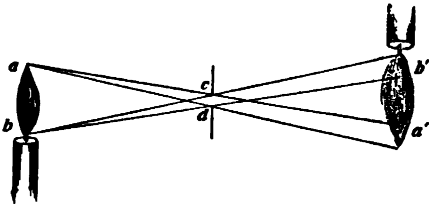

FIG. 202.—Light through small apertures.

A Camera made from a Small Pasteboard Box.—A hole scarcely one tenth of an inch broad is made in the cover of a small pasteboard box and a window about two inches square is cut in the bottom of the box; over this the thinnest tissue paper is pasted. A candle flame is placed before the small hole about an inch and a half distant. An inverted image of the flame appears upon the tissue-paper screen. This is seen much more plainly when a dark cloth, such as photographers use, is thrown over the head to shut the outside light from the eyes and from the screen.

This box represents a camera, and although it has no lens it takes a very fair picture of a landscape when a sensitive plate, such as photographers use, is placed in the bottom of the box. This must be done in a dark room, and a cloth must be wrapped around the box to prevent light from getting in and spoiling the plate before one is ready to take the picture. In taking the picture the cloth is removed from the small hole—not from the rest of the box—for a brief interval and then replaced, and the plate is taken out of the box in a dark room and put into the developing solution which photographers use. Such a pasteboard box as the sensitive plates come in serves well for this kind of a camera.

A Picture received through a Keyhole.—In the evening one may get an inverted picture through a keyhole by going into a dark room and holding a thin piece of paper a foot or two from the keyhole of the door, while some one holds a lighted lamp about the same distance from the other side of the keyhole.

CHAPTER XXVII

REFLECTION OF LIGHT

283. **Laws of Reflection.**—The angle which a ray of light makes with the perpendicular to a reflecting surface at the point where the ray strikes is known as the *angle of incidence*, (*i*, Fig. 203). After reflection the ray makes a second angle with the perpendicular, known as the *angle of reflection*, *r*. Two simple laws are found to hold in all cases of reflection :

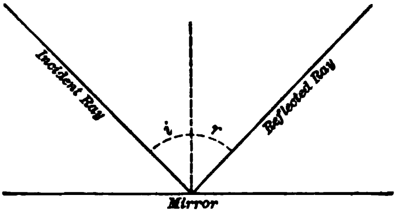

FIG. 203.—Law of reflection.

1. The angle of reflection is equal to the angle of incidence.

2. The incident ray, the perpendicular, and the reflected ray are in the same plane.

Heat rays are reflected in the same way. A billiard ball sent against the cushion tends to return according to the same law; other causes, however, operate to change the direction in this case.

284. **Images in Plane Mirrors.**—If such a reflected ray enter the eye, it produces there an image of the point from which it has come, but the image will not seem to be in the

direction of the incident ray, but will appear *back* of the reflecting surface as far as the real object is in front of it, and in the direction of the reflected ray produced. Such an image has, of course, no real existence. All the images produced by plane mirrors are of this character. They are constructed as follows:

Let *M R* (Fig. 204) be the surface of a plane mirror, and let *a* represent an object in front of it. We may locate the point where we imagine the image to be as follows: Consider any two rays passing from *a* to the mirror as *a c* and *a d*. They will be reflected in obedience to the first law, the angle of reflection, in both cases equaling the corresponding angle of incidence. Producing the reflected rays, they are found to meet at *a'*, as far back of the mirror as *a* is in front of it.

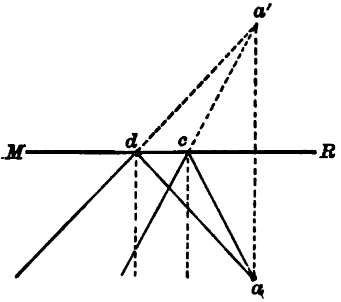

Fig. 204.—Location of image.

However complicated the object may be, its image is found in precisely the same way, practically by dropping perpendiculars from various points in an object to the mirror, and extending them to the rear as far as the actual points are to the front. Fig. 205 shows how rays of light will pass from *a* and *b*, the two extremities of an object, to a mirror, *M R*, and be reflected from the mirror to the eye of the observer at *e*, the image of the object appearing at *a' b'*. The image, while

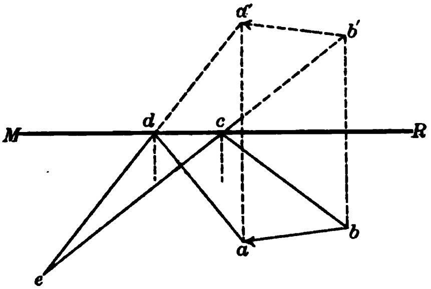

Fig. 205.—Location of image.

resembling the object in every other particular, is reversed.

285. Concave Mirrors—Principal Focus and Conjugate Foci.—Let *a o b* (Fig. 206) represent a concave mirror, and let rays of light, *S a* and *S b*, fall on its surface parallel to the principal axis, *d o*. If *d* be the center of curvature of the mirror, lines drawn from *d* to any point on the surface of the mirror will be perpendicular at that point. Hence any ray, *S a*, will be reflected to a point *F*, so located that *S a d* equals *F a d*. All parallel rays will be approximately reflected to *F*, which is called the *Principal Focus* of the mirror. Conversely, all rays originating at *F* will be reflected parallel to the principal axis *d o*.

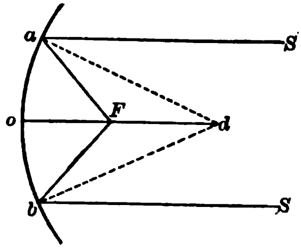

FIG. 206.—Reflection by a concave mirror.

Rays of sunlight may be considered parallel. They may be collected at *F*, which would thus be a center of great heat. This may be shown experimentally by turning a concave mirror toward the sun and finding *F*.

Conjugate Foci.—A source of light must be infinitely distant to send parallel rays to the mirror. Let us consider a nearer source of light, such as a candle at *a* (Fig. 207). The rays are divergent, and after reflection will be gathered to some point, *f*, farther from the mirror than the principal focus is. Conversely, rays originating at *f* would, after reflection, be gathered at *a*. Points so related as *a* and *f* are called *Conjugate Foci*, since they are interchangeable.

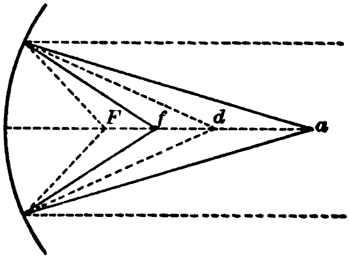

FIG. 207.—Conjugate foci.

286. Enlarged Images formed in Concave Mirrors.—In Fig. 208, ab represents the curved mirror, d is the center of its curve, the eye is supposed to be at e, and mn is an object. A ray of light from m reaches the eye by being reflected at c so as to make the angle of incidence, mcd, equal to the angle of reflection, dce. And it appears that, of all the rays of light which pass out from m and fall upon the mirror, this is the only one which may reach the eye. One should convince himself of this fact by drawing a series of diagrams showing the course which various rays from m to the mirror will take upon being reflected according to the law. The image of the point m appears to be behind the mirror in the direction ec, but the distance of m' from c is determined by the imagination, which differs with different people. In this book m' has been located so that $m'c$ shall be equal to mc, because this seemed to be as reasonable as any other conclusion, and it is a convenient measurement. In like manner the image of each of the points n, o, and p will appear behind the mirror at n', o', p', the extremities of lines ec''', and ec' and ec'', extended so that $c'''n'$, $c'o'$, and $c''p'$ shall be equal to $c'''n$, $c'o$, and $c''p$ respectively. The angles of incidence and reflection are in every case

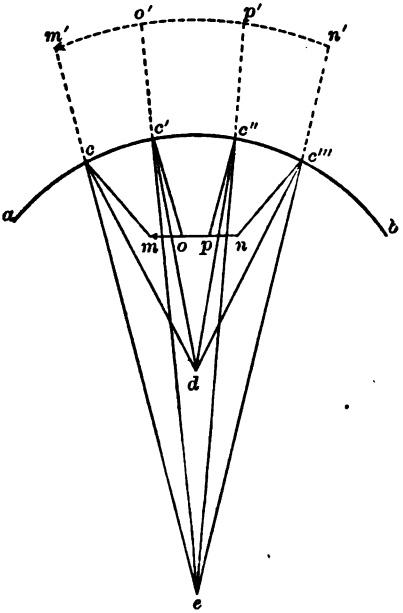

FIG. 208.—Enlarged images.

equal to each other. The image appears curved and enlarged. It appears enlarged both because it seems to subtend a greater visual angle, and because it seems to be farther distant than the object; it appears curved for reasons which are given in section 290.

287. **How an Inverted Image is formed in a Concave Mirror.**—In Fig. 209, *m n* represents a vertical line across the face, *e* the position of the eye, *a b* the mirror, *d* the center of the curve, *c* and *c'* the places upon the mirror where the rays of light from the points *m* and *n* respectively are reflected to the eye. Of all the rays of light which pass out from *m*, the one which meets the mirror at *c* is the only one which can be reflected to *e*, because it is the only one which can make the angle of incidence, *m c d*, equal to the angle of reflection, *e c d*. Hence the image of the point *m* will appear in the direction *e c*, and that of *n* in the direction *e c'*. The image *m' n'* will therefore represent the object turned end for end or inverted, and the image appears to be located about as far behind the mirror as the object is in front of the mirror. It does not appear curved in this case. For a discussion on this point see section 290.

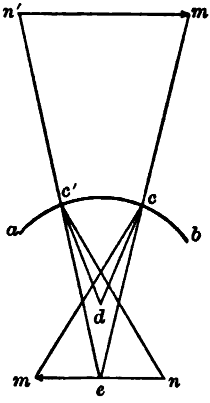

FIG. 209.—Inverted images.

When the mirror is near the face an upright image is seen, which grows rapidly larger as the mirror is moved farther away. The image soon becomes very indistinct, some parts appearing double, and then an inverted image of large size appears, which grows smaller as the mirror continues to move farther away.

The reason for this will appear to any one who will take the trouble to draw a series of diagrams after the plan of Fig. 209, in which the object *m n* shall be represented in various positions, some of which shall be between the center *d* and the mirror. It will be found that direct images will be produced in all cases where *e* is between *d* and the mirror, and that inverted images are produced when *e* is farther from the mirror than *d* is, and that the nearer *e* is to *d* the larger is the image.

288. **Diminished Images formed in a Convex Mirror.**—Fig. 210 represents a case where the convex side of the mirror is turned toward the face. The image always appears direct, always smaller than the object, and grows smaller as it recedes from the mirror. The figure represents the relation of the image to the object for one single position. It will be found to be instructive to make a series of diagrams for various positions which the object may occupy.

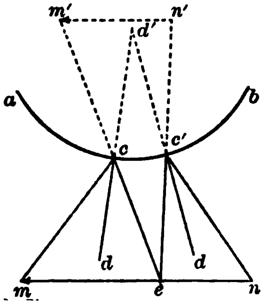

Fig. 210.—Diminished images.

289. **A Silver Spoon as a Concave and a Convex Mirror.**—The bowl of a bright silver spoon gives images that are enlarged or diminished in some directions more than others—i. e., the image is not a symmetrical representation of the object, as it always is when a true spherical mirror is used. This is due to the fact that the bowl of the spoon has a curve of a smaller circle from side to side than from end to end. A little experimenting with a piece of bright tin by bending it more or less while observing one's face in it will reveal the fact that in the case of convex mirrors the image always grows smaller as the mirror becomes more convex; but, in the case of concave mirrors, as long as the object is farther from the mirror than the center of the curve, the image grows smaller as the mirror becomes more concave; if, however, the object is situated between the mirror and the center of the curve, the image *enlarges* as the mirror

becomes more concave. This latter condition is never realized when one observes his face in the bowl of a spoon. A series of drawings like those represented in Figs. 209 and 210, in which the curve of the arc *a b* shall vary, will furnish an explanation of these phenomena.

290. **A Curved Image from a Straight Object.**—The image of a straight object appears curved in either convex or concave mirrors only when the object is very near to the mirror. It would appear, referring to Fig. 208, that, under these conditions, the mind instinctively conceives $m' c$, $o' c'$, $p' c''$, and $n' c'''$ to be respectively equal to $m c$, $o c'$, $p c''$, and $n c'''$, and that it is unable to recognize that relationship when the object is more remote from the mirror. This may be due to the fact that when the object is far from the mirror its image must be looked at very nearly in the plane of its curve, if it has one, and the eye fails to recognize the curve, just as it can not see the curve of a circle when looked at edgewise.

CHAPTER XXVIII

MISCELLANEOUS OBSERVATIONS ON REFLECTION

291. **How Daylight is diffused.**—Every one knows that mirrors reflect light, but few, if any, appreciate what a tangled lot of reflected and re-reflected rays we are using continually. All things reflect light to a greater or less degree.

It is easy to see that, although the direct sunlight is parallel and travels in straight lines, it scarcely travels far after it reaches the earth without meeting various objects which reflect it in all possible directions and into every nook and corner.

292. **Halos about Street Lights and the "Circle around the Moon."**—A beam of sunlight passing into a dark room is made apparent by particles of dust which reflect the light to the eye. If one takes a piece of glass and breathes upon it to bedew it with moisture, and holds it very near to the eye while looking through it at a candle flame, the flame will have the same appearance as the street lights do upon foggy nights. The small particles of moisture reflect light as the particles of dust do. These, distributed everywhere in the atmosphere, reflect the light of the moon at night, but only those occupying certain positions with reference to the observer can reflect light to his eye. This phenomenon may indicate the presence of much moisture in the air, but that does not always presage a storm.

293. **"The Sun drawing Water."**—The phenomenon which some people call "the sun drawing water" is pro-

duced by particles of dust or moisture in the atmosphere reflecting sunlight and marking the path of sunbeams which pass out from behind a cloud. These sunbeams are frequently seen in the latter part of the afternoon shooting upward toward the zenith as well as downward toward the horizon. People who suppose they are streams of water can not take the trouble to consider the difficulties which might appear to be counter to such a supposition.

294. **Illumination of Clouds at Sunset.**—Clouds, like the moon, catch the sunlight and reflect it to us after sunset. We see them best when the direct sunlight is shut off from our eyes by the horizon, but is still shining upon the clouds, just as we see the moon after the sun has gone out of our sight, but is still shining upon it.

295. **Moonlight and the Phases of the Moon.**—We are wholly unable to see an object unless light comes from that particular object to the eye. The moon is visible only when the sun shines upon it, and only that portion of it is visible upon which the sun shines, excepting that the dark part of the new moon is slightly illuminated by light reflected upon it from the earth, and is somewhat visible by this light being reflected back again from the moon to our eyes.

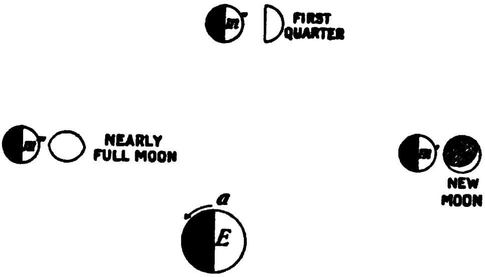

FIG. 211.—Phases of the moon.

Fig. 211 is intended to explain the phases of the moon. Sunlight is supposed to come from the right-hand margin of the page in parallel lines and illuminate the right half of m', m'', and m''', which represent the moon in three positions—in the western horizon, in the zenith, and in the eastern horizon. E represents the earth, the right half of which is also illuminated by sunlight; a represents the position of an observer upon the earth.

Suppose the observer looks at the moon when it is in the position m'; the earth meanwhile is turning over in the direction indicated by the arrow, carrying the observer into the darkened portion where he no longer sees the direct sunlight. The sun appears to sink below the western horizon, but the moon is still a little above the horizon, and he sees a little of the side of it which the sun is shining upon, and it appears crescent-shaped and is called the *new moon.* About a week later, at the same time in the day, when he looks for the moon he will find it overhead in a direction ninety degrees from that of the sun, and it will appear like a semicircle. It is then said to be in *first quarter.* In another week at sunset he will find the moon upon the eastern horizon showing a complete circle, when it is called *full moon.* These appearances of the moon are called *phases of the moon.*

296. **How the Dark Part of the New Moon is made Visible.**—If we could transfer ourselves from the earth to the new moon, we should be able to look back upon the earth as upon a *full* moon four times as broad as the moon itself ever appeared to us from the earth, and reflecting sixteen times as much light, because its apparent area would be sixteen times as great as that of a full moon. The earth, then, shines so brightly upon the darkened side of a new moon that it illuminates it sufficiently to make it visible from the earth when the atmosphere is very clear. Clouds in our atmosphere might interfere with the earth's giving so much light to the moon as stated above, and they interfere with our receiving the light reflected back again from the moon. Whenever, therefore, we see the dark portion of the moon we may remember that we are receiving into

our eyes sunlight which has been first reflected from the earth to the moon and then back again from the moon to us. If we could visit the moon in "first quarter," the earth would appear to us as a larger moon in the "first quarter"; and if we could visit the full moon, the earth would appear as a very large new moon. In neither of these cases does the earth reflect light enough to the moon to make its dark part visible to the earth.

Venus at all times, as seen through a telescope, appears like a new moon.

297. **Why are Transparent Objects and Very Good Reflectors so nearly Invisible Themselves?**—It seems probable that if an object could be either perfectly transparent or a perfect reflector it would be wholly invisible. When a bottle is entirely filled with very clear water it often appears empty. Window panes may be so clear that it is difficult to tell whether they are present or wanting. Air is invisible because of its transparency. Moreover, a mirror is often well-nigh invisible itself because it is so perfect a reflector of light. Most substances reflect a part only of the light which falls upon them, and transmit or absorb the rest. A glass put over a picture often transmits too little light and reflects too much to serve well its purpose. The same is frequently true of a show window. It is particularly so the more obliquely one attempts to look through them. It is also a matter of familiar experience that, when one attempts to look through a window from the outside, the farther he is from the window the greater is the proportion of reflected light, and the nearer he is to the window the greater is the proportion of transmitted light.

Objects which are nearly invisible, either because they are good reflectors or because they transmit light well, become readily visible if covered with dust or moisture or are scratched, or if in any way the surface is made rough. A bright tin reflector may be scoured with sand or scratched with a file so that it will no longer reflect an image. A glass mirror might be treated in the same way. Transparent glass, if treated in this way, loses its transparency and becomes "ground glass." A quiet body of water which acts like a mirror ceases to do so when ruffled by a breeze.

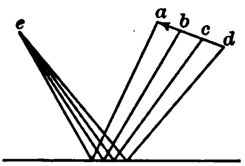

FIG. 212.

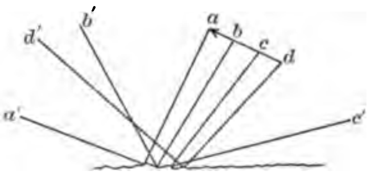

FIG. 213.

The accompanying figures (212 and 213) present an explanation for this fact.

298. **Visibility of Print upon Glazed and Unglazed Paper—Drawings upon Rough and upon Highly Polished Surfaces.**—All objects have a somewhat ruffled surface, and it seems probable that they are themselves made visible, not by the light which they transmit or reflect from a smooth surface, but by the rays which they scatter. Thus, in Fig. 212, the rays of light which meet the eye at *e* from the various points of the arrow *a b c d*, being reflected in regular order, make the observer conscious of the arrow, but not of the mirror; on the other hand, in the case represented in Fig. 213, a jumble of rays from a great variety of objects is reflected to the eye, and the mind, not being able to form an image of any object beyond the mirror, traces the light only so far as the mirror itself, and is conscious of that alone.

It is much easier to read from a rough page than a glossy one. Drawings and paintings show much better from rough than from highly polished surfaces. Polished blackboards would be of little use. Shading a picture with crayon is only a matter of diffusing the light which it will reflect.

299. Twilight.—Every one who is at all thoughtful concerning natural phenomena must sometimes ask the question, Why, after the sun has set, does light linger so long and darkness come so slowly? This period between day and night we call *twilight*. It occurs in the morning as well as in the evening. It lasts much longer in summer than in winter. We may properly consider one of the causes of twilight in this chapter; it is reflection. In Fig. 214, *E* represents the earth. Sunlight comes from the right-hand side. *U U* is the umbra, *a a a* is the atmosphere. The ratio of its depth to the diameter of the earth is greatly exaggerated, however. The arrow shows the direction in which the earth rotates. *O* is the position of an observer for whom the sun has set, and he is now in the region of twilight. Clouds and innumerable particles of moisture and dust floating in the atmosphere above still catch the sunlight and reflect it down upon him. In the morning he will enter another such region of twilight, represented at the lower margin of the figure, before he receives the full light of the sun.

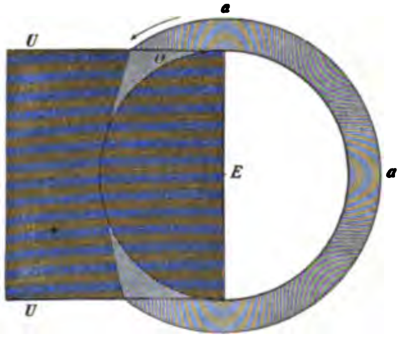

FIG. 214.—Twilight.

CHAPTER XXIX

REFRACTION OF LIGHT

300. Refraction of Light defined and illustrated.—The fact that rays of light are *bent* in passing through various transparent substances is illustrated on every hand. *This bending of rays of light is called refraction.* It only requires that one should be fairly attentive to what he sees about him to become familiar with most of the phenomena of refraction. At the dinner-table one may see objects through his tumbler of water, not only apparently displaced, but also enlarged, distorted, and even inverted horizontally. The handle of a teaspoon in the tumbler of water may appear to be broken. A bubble or a crack in a window pane may make an object outside appear to be broken, displaced, or distorted. An inkstand, a paper-weight, a beveled mirror, or other household articles may give prismatic colors.

When a beam of light passes obliquely from one medium to another of different density, as from air into water, or air into glass, it suffers refraction. The entire beam does not enter the second medium. A part of it is thrown off as a reflection. The part that enters the second medium is not all refracted. A portion of it is absorbed and appears as heat. The portion that is refracted is subject to definite laws, just as the reflected part is.

Refraction may be conveniently studied by means of a glass vessel with parallel sides, on which a circle is painted (Fig. 215). The vessel is filled with liquid, say water, up to the horizontal diameter of the circle. A lamp is placed at *L*, so that its light will strike the water at the center of the circle. If the experiment is performed in a dark room, it will be plainly seen that where the light strikes the water its rays are bent toward the perpendicular.

301. **Index of Refraction.**—The amount of refraction is measured in this way: $a\,o$ and $d\,o$ being made equal, the distance of each of these points from the perpendicular is measured and compared:

$$\frac{a\,b}{d\,c} = \frac{4}{3} = 1.33.$$

This value is called the index of refraction. It is found to be constant for any two given media, however much the obliquity of the ray of light may change —i. e., so long as the two media remain air and water, we may change the direction of the ray $a\,o$, and consequently the value of $a\,b$, never so much, $d\,c$ will likewise change so as to be three fourths of $a\,b$.

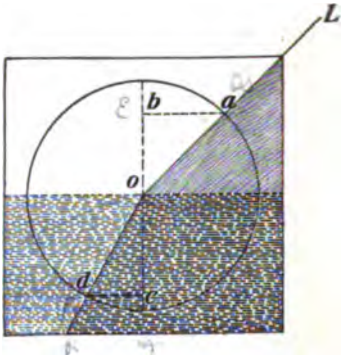

FIG. 215.—Refraction.

The index of refraction varies with different media. For light passing from air into ether it is 1.36; into alcohol, 1.37; into turpentine, 1.47; into crown glass, 1.53; into flint glass, 1.63; into carbon bisulphide, 1.67; into diamond, 2.75.

It is manifest from this that optical density is not the same as ordinary density; for, although ether, alcohol, and turpentine are all lighter than water, they have a larger index of refraction. This is illustrated in Fig. 219. The following laws are found to hold:

1. The incident ray, the perpendicular, and the refracted ray are in the same plane.

2. When light passes from an optically rarer into a denser medium obliquely to the surface, which is between

the two media, it is bent toward the perpendicular to that surface; or, conversely, if it passes from a denser into a rarer medium, it is bent away from the perpendicular.

3. The index of refraction is always a constant value for any two given media, however much the obliquity of the ray may change.

302. **Cause of Refraction.**—These facts are purely experimental, and therefore quite independent of any theory. But we have now to inquire why the ray is bent a definite amount if oblique, and is not bent if perpendicular. Suppose a beam of light with a wave front, *l l'* (Fig. 216), to strike obliquely against the surface of water, *s s*. It has been found by experiment that light travels one third again as fast in air as in water. Consequently the whole wave is retarded in the water. But all portions of the wave front do not enter the water at the same time. When *l* reaches *ss*, *l'* is still some distance away. If, now, *l* traveled as fast as *l'*, the beam would pass into the second medium without any bending, as indicated in the dotted lines. But this is not the case; while *l'* passes to *s s*, *l* can only go three fourths as far—that is, to *h*—and hence the wave front swings around to *h h'*, and the beam itself, which must always be perpendicular to the wave front, takes the new direction shown, bent toward the common perpendicular. When the beam is perpendicular to *s s*, the wave front *l l'* is equally retarded along its entire length, and consequently there is no change of direction.

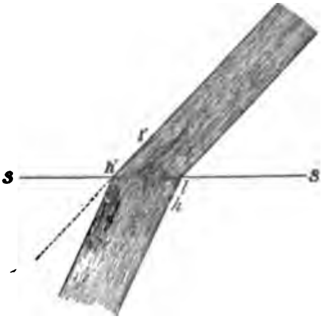

FIG. 216.—Refraction.

303. **Value of the Index.**—The numerical value of the Index of Refraction is always the ratio of the velocity of

light in the first medium to the velocity in the second. When, therefore, light passes into a medium of greater density, the index is always greater than one, and the ray is bent *toward* the common perpendicular. When light passes into a medium of less density, the index is always less than one, and the ray is bent *away* from the common perpendicular.

When the direction of a beam is reversed, the second becomes the reciprocal of the first. Thus, the index, when light passes from air into water, is $\frac{4}{3}$; but when light passes from water into air, the index is $\frac{3}{4}$.

304. **The Critical Angle.**—It follows from all this that a ray of light can always pass from a rare into a dense medium, because it is bent *toward* the common *perpendicular;* but the ray can not always pass from a dense into a rare medium, for if the ray should be bent *away* from the common perpendicular more than 90° it would fail altogether to emerge from the denser medium. No ray of light can pass from water into air if it makes a greater angle with the perpendicular than 48° 35′.

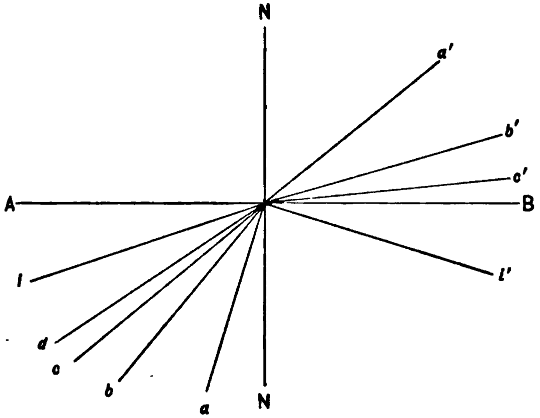

FIG. 217.—Critical angle.

Referring to Fig. 217, let *A B* represent the surface of water. A ray of light starting from *a* will be bent so as to reach *a′*, likewise those which start from *b* and *c* will reach *b′* and *c′* respectively, but one which starts from *d* would be bent so as to pass along the surface through *B*, and one which starts from *i* would be bent so as to return beneath the surface of the water to *i′*.

305. **Total Reflection.**—We may well be interested to inquire what becomes of rays which make greater incident angles than the critical angle, and which consequently can not emerge.

They are reflected, and since the reflection is complete, it is called *total reflection.* Could we stand at the bottom of a pool of clear water and look upward, we should see objects on the surface of the water within a cone which had our eye for its apex, and whose elements made an angle of 48° 35′ with its axis. Beyond the circular base of this cone we should see a perfect mirror, which would reflect objects lying on the bottom of the pool. The same effect on a small scale may be seen when we look at the underside of the surface of water in a clear tumbler, provided the angle of vision be greater than the critical angle. The surface appears like a burnished mirror. A silver spoon or a bright coin will give a brilliant image. For the same reason, water in a test-tube seems covered with a film of silver when looked at from below.

306. **Applications.**—Refraction is the source of many illusions. Bent rays of light make objects appear where they are not. The sun, moon, and stars, when near the horizon, are elevated about half a degree by the refraction of the earth's atmosphere. This is equal to the apparent diameters of the sun and moon. Sticks and other objects partly immersed in water appear bent at the surface (see Fig. 218). Clear water appears less deep than it really is. The hot air over the surface of a desert bends the rays of light and produces the mirage, the appearance of reflection in water.

Precious stones owe their brilliancy to high refractive power, and consequently to total reflections from the facets on the other side. The critical angle for the diamond is 23° 53′. All the light that passes into the diamond, and strikes any of the facets at angles greater than this, suffers total reflection within the stone, and finally emerges in pencils of light, which produce the magnificent fire and sparkle of the gem. Many of the rays of light are so refracted as to produce prismatic colors. The diamond owes all its brilliancy to the cutting, for in its natural state it is dull.

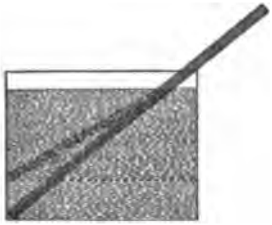

FIG. 218.—Refraction.

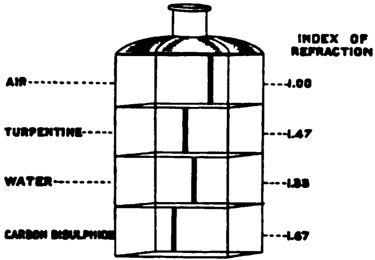

FIG. 219.

Our heaviest flint glass has a critical angle of 35° 37′. Artificial diamonds made of this material must, therefore, have much less brilliancy than the real stone. If we could make a glass as transparent as the diamond, and having an equally high refractive index, we should have an equally brilliant gem.

Refraction of light enables us to see colorless and transparent fluids. Fig. 219 represents a bottle which contains three colorless and transparent liquids. They remain separate from one another as oil and water do. Carbon bisulphide is at the bottom, upon this floats the water, and upon the water floats the turpentine. A straight line is drawn vertically upon the back face of the bottle, and this, as seen through the liquid obliquely, appears as a broken line, by reason of the differing powers of refraction of the liquids.

The fact that we may distinguish between these various liquids is due to the variation in their refracting power. Air refracts light, and cold air more than warm air. This is the reason why we can see hot air rising above a stove. Small currents of warm air pass up through the cold air, and rays of light coming from objects seen through these currents of air are made to quiver by reason of rapid changes in their refraction. Something similar appears when one of the liquids mentioned above is poured in a small stream into another in the bottle. It is well shown by pouring glycerin into water.

Refraction enables us to see the sun two minutes after it has set and two minutes before it rises, hence it has the effect of lengthening the day four minutes. Reflection, by producing twilight, lengthens the day several hours. We may see the sun ten minutes after it has set, on account of both refraction and the velocity of light, but on the same account we do not see it until six minutes after it has risen.

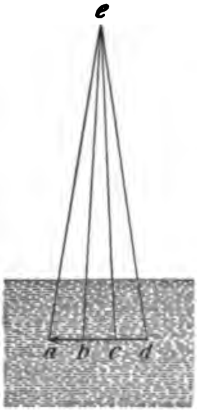

FIG. 220.

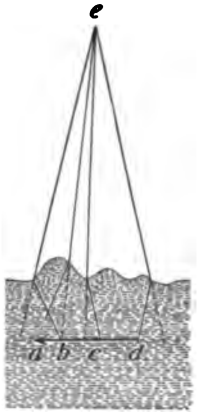

FIG. 221.

A body of clear water, which when calm may reveal objects at great depths, will not do so when the surface is disturbed by a breeze. This is due to refraction, as will be seen from Figs. 220 and 221. In Fig. 220 each point in the object *a b c d* under water sends its light in regular order to the eye, *e*, held above the water, but in Fig. 221 these rays are so bent as to give a confused image.

307. **Refraction in Prisms.**—The path of a ray of light in passing through a prism is illustrated in Fig. 222. Suppose *B E* to be an incident ray upon the face of a glass prism. After refraction the ray will take the direction *EJ*, being bent toward the perpendicular at *E*, and will suffer a second refraction at *I*. Here the ray is passing into a less dense medium, and must consequently be bent away from the perpendicular, and must take some such direction as *I S*. From the nature of the case, the ray is always bent toward the base of the prism—that is, toward the thicker part.

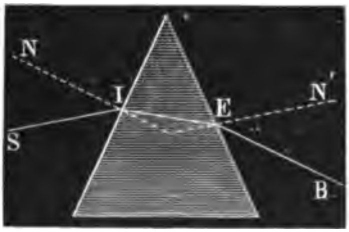

FIG. 222.—Refraction by a prism.

308. **Enlarged Images produced by Refraction.**—A cross-section of a prism is represented in Fig. 223; *m n* represents an object, and *e* the position of the eye. The object appears to be enlarged to the size of *m' n'*, which may be measured and perhaps found to be half as large again. The ratio of the size of the image to the size of the object is expressed thus:

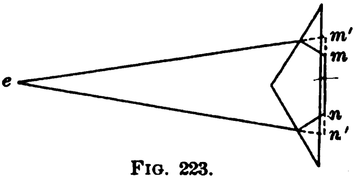

FIG. 223.

$$\frac{m'\,n'}{m\,n} = \frac{15 \text{ mm.}}{10 \text{ mm.}} = 1.5.$$

309. **Different Kinds of Lenses and the Way they refract Light.**—If the prism mentioned above were slightly modi-

fied in shape so that its cross-section would look like Fig. 224, *b*, we should call it a *lens*, and, since one of its surfaces

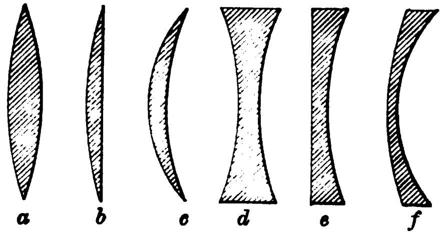

FIG. 224.—Typical lenses.

is plane, while the other is convex, it would be called a *plano-convex* lens; if the plane surface were made convex also, it would be called a *double-convex* lens (*a*); if one surface were plane while the other were concave, as represented at *e*, it would be a *plano-concave* lens; and if both surfaces were concave, it would be called a *double-concave* lens (*d*).

After what has been said, it is a simple matter to understand how rays of light will be bent in passing through these lenses. The principle to be borne in mind is that when a ray passes from air into glass it is bent toward the perpendicular, and when it passes from glass into air it is bent away from the perpendicular. It is evident that the lens represented at *e*, for example, makes the image appear smaller than the object, and that the lens at *a* has the greatest magnifying power.

310. **Inverted Images produced by Refraction.**—In Fig. 225, *a b* represents a lens, *m n* represents an object, and *n a e* and *m b e* are lines of light which pass from the extremities of the object through the lens to the eye, which is supposed to be situated at *e*. The image *m′ n′* appears to be inverted. The reason for this is not hard to find. Rays of light pass out from the point *m* in all directions. One ray takes the direction of the line *m b e*. The mind

conceives that it sees *m* in the straight line *e b* at *m'*. For the same reason the image of *n* appears at *n'*—i. e., the image of the arrow appears to point in the opposite direction from the way the arrow itself points. None of the rays of light which start from the points *m* and *n* and fall upon the lens can reach the eye except those which pass through *b* and *a*, as represented; all others will be bent, according to the law of refraction, so as to pass one side or the other of the eye.

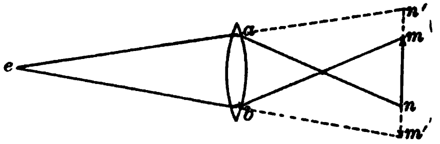

Fig. 225.—Enlarged and inverted image.

311. **The Path of Rays of Light exhibited by Crayon-dust—Measuring the Focal Distance of a Lens.**—When the lens is held in sunlight and plenty of dust is made to float in the air around it, by beating blackboard erasers or dusty clothing near it, the rays of light are easily traced by means of these reflecting particles, and they are seen to meet and cross, forming two cones of light as represented in Fig. 226. The points where the apices of the cones meet is the principal focus, and its distance from the lens may be measured.

These cones of light may be traced by using a screen. When the screen is brought against the face of the lens, the circle of light upon it is about the size of the lens. If the screen is placed halfway between the lens and the focus, the circle of light has about half the diameter of the lens;

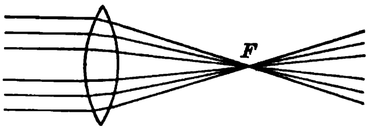

Fig. 226.—Principal focus.

its area is therefore one quarter as great as in the first position, and the intensity of its light four times as great. When it is placed one quarter of the distance from the focus to the lens its circle of light is one quarter as broad and its area one sixteenth as great and the intensity of its light sixteen times as great as at the first position. At the focus it is a point of light of dazzling brightness, the heat of which is sufficient to burn a hole in paper when the experiment is tried in the brightest sunlight. The focal distance can be readily measured by placing the screen where the cross-section of the cone of light is nearest to a point and measuring the distance from the lens to the screen.

312. **Pictures formed at the Focus of a Lens.**—When a lens is held before a screen at its focal distance, an inverted picture of distant objects is formed upon the screen. The objects in this case are so far away that rays of light from them are nearly parallel. When objects are brought nearer to the lens the screen must be moved farther away from the lens in order to receive the picture. A candle flame is a good object to experiment with, because it furnishes brighter rays of light than are reflected from objects in general. When the screen is placed so that a picture of the candle is formed upon it by the lens, the candle and screen occupy the positions of one pair of conjugate foci. If either one of these is brought nearer to the lens, it is found necessary to remove the other farther away, and *vice versa.* When a photographer takes a picture of a person sitting very near his instrument, he draws out the camera so as to move the plate which is to receive the picture farther away from the lens; and when the person sits farther from the instrument, the operator moves the plate nearer to the lens by contracting his camera.

313. **To illustrate how a Lens forms a Picture.**—It may be easy to see how a lens magnifies and inverts, but why should it form a picture at all?

If an object were placed before a screen without a lens between them, light would be reflected from every point on the object to every point on the screen, so that each point on the screen would receive an equal amount of light from each and all points of the object. In order to have a picture formed, each point of the object must send its light to one, and only one, point on the screen. This is brought about by the lens, as will be seen by reference to Fig. 227. All the rays of light which pass out from the point *m* and fall upon the lens are collected at the point *m'*. This is one pair of conjugate foci. In the same way all the rays which pass from *n* to the lens are collected at *n'*, and these form another pair of conjugate foci. But when the screen is placed in focus for the light from *m* and *n* it is found to be out of focus for light from the points *o* and *p*, whose conjugate foci are found to be farther away from the lens than *m'* and *n'* are, because the points *o* and *p* are nearer the lens than *m* and *n* are. This consideration is important only when the object is near to the lens, for only then would the difference between the distance of *m* and *o* from the lens be appreciable. If, however, a photographer should attempt to take a picture of a group of persons formed in a straight line having his camera near the group, the individuals at the extremities of the group could not be in focus at the same time with those in the center.

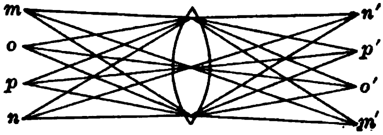

Fig. 227.—Conjugate foci.

314. **Material of Lenses.**—The lenses used for optical purposes are made of flint glass. This is a double silicate of potash and lead. The lead makes the glass much more

dense, and gives it, consequently, a greater refractive index. For the same reason flint glass is used for the cut glass of tableware and toilet articles. Their cut facets have a very brilliant effect on account of refraction.

315. **Familiar Illustrations of Lenses.**—Very many objects act as lenses. When the eye is held near to a drop of water upon a window pane, an inverted picture of the outside world is seen. If the sun is shining through it, a piece of paper held near it will show that the rays are made to converge to a point. Fish globes, and the globes used in drug-store windows, give magnified and inverted pictures. The neck of a small bottle magnifies so that if the bottle is filled to the neck with water containing microscopic objects, many of them may be seen. The animals which are usually found in vinegar may be easily seen if the vinegar cruse is filled to the neck.

316. **The Simple Microscope.**—A microscope is an instrument for enabling us to see very small objects by producing magnified images of them. The simple microscope is usually a double-convex lens, and in use is so placed that the object to be viewed is back of the lens at a distance less than the focal length. Under these conditions we have a magnified and erect image. The construction of the image is of course purely imaginary. It has no real existence. But the imagination has the power of constructing such an image, just as it has the power of constructing images back of a looking-glass. The rays that come from the object are bent by the lens, as shown in Fig. 228, and enter the

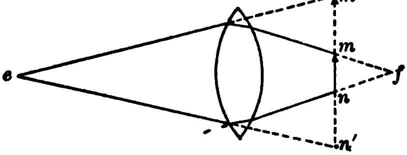

FIG. 228.—Simple microscope.

eye at a wider angle than the direct rays would. This angle, known as the visual angle, determines the apparent size of objects. The simple microscope increases this angle, and consequently makes the object seem larger.

317. **Compound Microscope.**—In its simplest form the compound microscope consists of two lenses, the objective *c d*, and the eyepieces *a b* (Fig. 229). The two are mounted in a tube on a suitable stand. In this way we have a double magnification, and the power of a compound microscope is equal to the product of the magnifying powers of the objective and the eyepiece. The image is inverted.

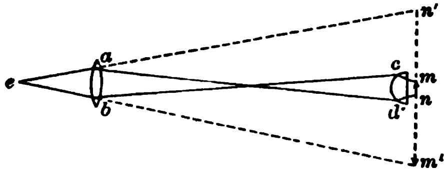

FIG. 229.—Compound microscope.

In practice the compound microscope is very complicated in its construction. Both eyepiece and objective are themselves compound. In addition there are various accessories for biological, mineralogical, and technical work that make the instrument quite an elaborate piece of mechanism.

318. **The Telescope** is an instrument for viewing objects from afar. There are two classes—the reflecting and the refracting. The latter are of the greater importance, but the former have played a historic part in astronomy, and are still doing good service in both England and France. The refracting telescope is, in its elements, very similar to the compound microscope. It consists of an objective and eyepiece.

In astronomical telescopes it is desirable that the objective should be as large as possible in order to include much light. The mechanical difficulties in the way of producing large refractors are very great, but they have been successfully overcome. The construction of such an instrument involves the combined skill of several nations. The glass is usually cast in France. Most of the large lenses, so far, have been ground by the Clark Brothers, in Cambridge, Mass. The mountings and requisite machinery are made where most convenient. The largest lens yet made is the giant objective cast and ground in France and now at the Paris Exposition (1900); it is 50 inches in diameter. Next to this comes that of the University of Chicago, and is located at Lake Geneva, Wis.; it is 40 inches in diameter. Next to this comes that of the Lick Observatory, in California—91 centimetres, or 35.82 inches, in diameter.

319. **The Human Eye.**—Most wonderful of all optical instruments is the human eye, and also the most imperfect. Looking at the eye, what we see first is the transparent, bulging cornea, which is a modification of the outer coat of the whole eyeball, "the white of the eye," or the sclerotic coat (Fig. 230).

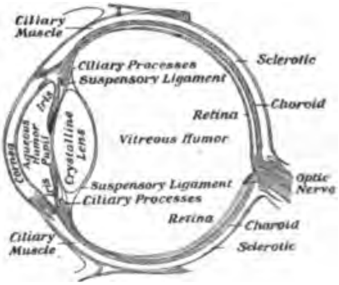

FIG. 230.—Section of the human eye.

Immediately back of the cornea there is a cavity filled with a liquid known as the aqueous humor. Back of this cavity there is a muscular screen, the iris, which is annular in form, and gives color to the eye. The opening in the iris is known as the pupil. Under the influence of strong light the iris contracts, and the pupil becomes very small, so as to shut out as much light as necessary. In the dark, or in subdued light, the muscles relax and the pupils become larger. Directly back of the iris is the crystalline lens. It is transparent, and tough and elastic. The interior of the eyeball is filled with a jellylike substance, the vitreous humor. The innermost lining of the eyeball is the retina, formed by an extension of the optic nerve leading directly to the brain. Between the retina and the sclerotic coat is a black pigment, the choroid coat.

In its operation the eye is quite similar to a photographic camera. The crystalline lens is double convex, and forms an inverted image on the retina. The retina may be compared to the sensitive plate of the photographic camera, and the pupil, or opening in the iris, which serves to admit more or less light, may be compared to the diaphragms, or stops, used for the same purpose in the camera. So far it is very simple and well understood. But our explanation ends here. As a physical fact, the image on the retina means simply light-waves of varying wave length and intensity, and these have varying effects upon the nerves of the retina. All these complex impulses pass by means of the optic nerve to the brain, and it is in the brain that we see. But how these nerve impulses get translated into a mental impression we are quite at a loss to explain. We have said that the human eye is one of the most imperfect of optical instruments. Few persons have perfect eyes.

Cataract is caused by the crystalline lens becoming opaque, and therefore ceasing to transmit distinct rays. Operations are sometimes successfully carried out by which the lens is removed altogether and sight restored, the humors in this case acting as the sole refracting medium.

The common defects of vision, such as short- and long-sightedness and astigmatism, result from structural defects. Clear vision requires that a distinct image shall be formed on the retina. As the object, the crystalline lens, and the retina are fixed in position, the focusing can only be brought about by a change in the curvature of the lens. This is a matter of muscular contraction, and in normal eyes is done so quickly and unconsciously that we pass from the contemplation of distant to near objects, and *vice versa*, without the least difficulty. Near-sightedness results from too great curvature of the lens, so that it forms images in front of the retina. It is remedied by the use of glasses which cause rays of light to diverge (Fig. 231). Far-sightedness, on the contrary, results from too little curvature of the lens, so that images form back of the retina. It must be remedied by glasses which cause rays of light to converge (Fig. 232). It is a universal defect of old age. Astigmatism means an irregular curvature of the cornea, by which the eye is never in focus for all objects in the field of vision, even at the same distance. It is remedied by special lenses combining spherical and cylindrical surfaces. Few people have eyes that are perfectly adapted for parallel vision. The muscular effect necessary to bring them to parallel is a most frequent cause of headaches.

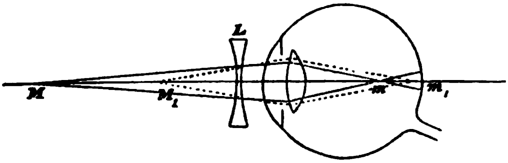

FIG. 231.—Double-concave glass for near-sightedness.

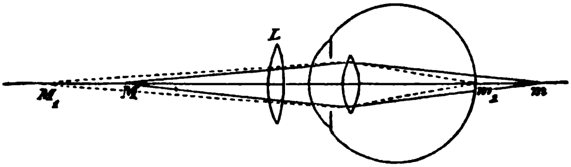

FIG. 232.—Double-convex glass for far-sightedness.

320. **The Spectrum.**—We have seen that the index of refraction is in reality the ratio of the velocity of light in the first medium to the velocity in the second medium, and we have assumed that we had to deal with homogeneous

rays—that is, rays of uniform wave length. But white light is heterogeneous, consisting of wave lengths varying from .0004 millimetres in the violet, to .0007 millimetres in the red. These different rays are found to have different indices of refraction, and to suffer unequal bending on passing into a second medium. In consequence, the various colored rays which, taken together, make a beam of white light, on passing through a prism are separated, so that the violet rays are on one side and the red rays on the other. If they be allowed to fall on a screen, we have the fine succession of rainbow colors known as the spectrum (Fig. 233).

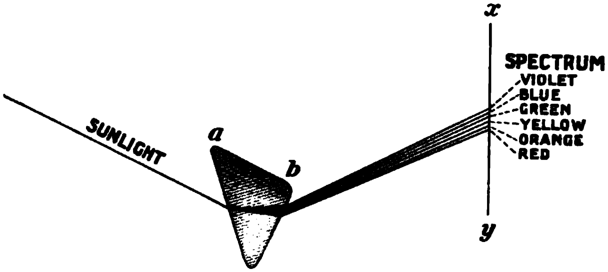

FIG. 233.—The spectrum.

Newton, in 1676, was the first to explain the matter. He distinguished seven primary colors, and named them violet, indigo, blue, green, yellow, orange, and red. It will be noticed, in looking at the spectrum on the screen, that the violet has been turned out of its path the most, and the red the least. The shorter violet waves are more retarded than the longer red waves in passing through the glass.

A single prism will give a spectrum, but the effect will be magnified by combining a succession of prisms, and so increasing the total dispersive power. The train of prisms may be arranged in a circle, so that the beam of light constantly changes its direction and constantly widens (Fig. 234). On the other hand, prisms may be combined in pairs, so as to neutralize one another (Fig. 235).

There seems to be no limit to the possible length of ether waves. To produce any effect upon us, however, they must fall within very well-defined limits. The longest ether waves apparently have no effect. As they shorten they manifest themselves as heat; as they grow still shorter they become visible as light, then as a source of chemical activity, and finally they again pass beyond the range of our sensations. We perceive only a small part of the possible waves.

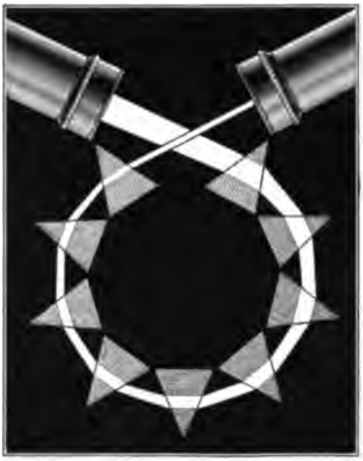

FIG. 234.—A train of prisms.

Color.—We should expect these varying lengths of wave to affect us differently, just as the different pitch in musical notes, which is due to difference in length of air waves, and such, indeed, is the case. Color is the name given to this difference of sensation, and depends wholly upon wave length. Ordinary sunlight contains waves of all lengths within the range

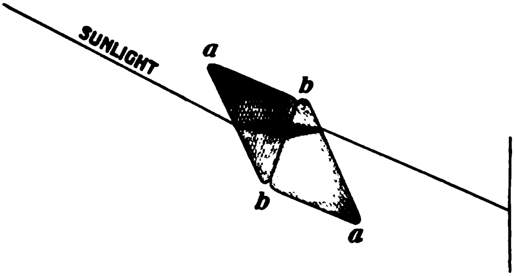

FIG. 235.—A pair of prisms.

of vision and is distinguished as white light. The range of vision lies between .0007 millimetres in the red and .0004 millimetres in the violet. The following table shows the wave length corresponding to the different colors:

	Wave Length.		Wave Length.
Red	.0007 mm.	Green	.00053 mm.
Orange	.0006 mm.	Blue	.00047 mm.
Yellow	.00058 mm.	Violet	.0004 mm.

321. **The Invisible Spectrum.**—At both ends of the spectrum we have a dark region, quite invisible to the eye, but manifesting itself by its effects. Beyond the visible red we have a region of dark heat rays, which manifest themselves if a delicate thermometer, such as a thermopile (see 271), be placed in their path. We call this the heat end of the spectrum, and the colors at that end are sometimes referred to as warm colors. Beyond the visible violet we have another dark region, that of the so-called actinic rays, which have the power of bringing about chemical reactions, such as decomposing the sensitive silver salts used on photographic paper, and of making certain fluorescent substances —such as fluor spar, quinine, and platino-cyanide of barium —visible in the dark.

The invisible spectrum has a far greater range than the visible. In musical terms we might say that the visible spectrum covers about one octave. The heat spectrum extends for *five* octaves below the red, and the actinic or chemical spectrum for *two* octaves above the violet.

We can easily imagine that the world would appear very different if our eyes were different in their power to perceive ether waves.

322. **Complementary Colors.**—To produce white light it is not necessary to have waves of all lengths present. It is found, indeed, that two colors, if properly chosen, will suffice. As these extinguish each other, they are called *complementary* colors. Thus, red and greenish-blue, orange

and Prussian blue, yellow and ultramarine, green-yellow and purple produce white light when taken in pairs. There appear to be three primary color sensations—red, green (slightly yellowish), and violet (bluish)—and when these are all excited at the same moment, the result is the sensation of white. No two of these primary colors can be complementary, for the third sensation would be lacking. But any one of the three is the complementary color of the result of the other two. Taking the pairs of colors mentioned above, this principle will be found to apply. Thus, greenish-blue contains both green and violet, and is therefore complementary to red; purple, containing both red and violet, is complementary to green-yellow, etc.

The phenomena of color are very fascinating and almost unending. In reality no objects are, properly speaking, colored. The sky is not blue, the grass is not green, the rose is not red. They appear so to us because of their effect on white light. The color ascribed to them is the color they reject. A bit of red glass is one that absorbs the complementary color, greenish-blue, and allows the red light to pass through, or else reflect it to us. If such a piece of glass be put into the fire, the red color remains so long as the glass is cooler than the fire—that is, so long as it is absorbing green. The color disappears when the glass has the same temperature as the source of heat back of it, for then the radiation emitted and absorbed just balance each other, If the glass be the hotter, it appears blue-green, for it is emitting more radiation than it is absorbing. In general, we may say that substances emit radiations of the same wave length that they absorb.

The Color Wheel.—The blending of several colors into one impression may be capitally shown by means of a rotating wheel or color-whirler (Fig. 236). Disks of colored cardboard may be attached and made to rotate with the wheel. Thus a disk having alternate sectors of black and white, when rotating appear a uniform gray. If the white sectors are larger, it will be a light gray; if smaller, a dark gray. So red and blue produce purple. Complementary colors produce white. A disk having all the colors of the spectrum, properly proportioned, will produce white. The various pairs of colors opposite to one another in the circle (Fig. 236) are complementary and will produce white when confused together by rapid motion.

Sunlight, according to Professor Rood, contains in 1,000 parts the following ingredients:

Red	54	parts.
Orange-red	140	"
Orange	80	"
Orange-yellow	114	"
Yellow	54	"
Green-yellow	206	"
Yellow-green	121	"
Green and blue-green	134	parts.
Prussian blue	32	"
Blue	40	"
Ultramarine and blue-violet	20	"
Violet	5	"

As the pigments used in coloring the pasteboard upon the color wheel are impure colors, one must not be disappointed if the impressions are somewhat muddy. They are, however, enough to the point to illustrate the truth of what has been said. The art of color mixing in painting is far from being the simple matter it might at first seem, chiefly because of the tendency to chemical change which most pigments have.

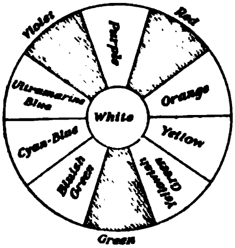

FIG. 236.—Complementary colors.

In modern picture windows, which in the hands of Tiffany and La Farge have become genuine works of art, the effects are often produced by doubling or even tripling the glass. Robes of royal purple are thus obtained by separate thicknesses of blue and ruby glass.

323. **Fluorescence and Phosphorescence.**—It is very plain that if by any operation we could change wave length of radiations, we should change their character. Retarding

rapidity of vibrations and increasing the wave lengths might change chemical rays to light rays and light rays to heat rays, or change light rays of one kind into those of another kind. Quite a number of substances possess this power. Sulphate of quinine solution in the ultraviolet emits a pale-blue light; uranium glass gives a brilliant green; fluorescein gives a beautiful green. The common mineral fluorite, CaF_2, has the same power, and hence the name fluorescence has been given to the phenomenon. The platino-cyanide of barium is even more powerful. Its ordinary color is a dull yellow, but in the ultraviolet it gives a magnificent yellowish-green light.

Phosphorescence, the power which certain substances have of emitting light in the dark after due exposure to strong light, is a similar property, but more persistent in character. The so-called "luminous paints," made usually of sulphide of barium, BaS, have this property, and serve to call our attention to the house number, the match box, and other articles usually sought for in the dark.

But of far greater importance than even these beautiful phenomena is the change of wave length which takes place by the absorption and radiation again which occur in all forms of matter, since upon these depend very largely the habitability of the globe itself. The light radiations from the sun are thus changed by the earth into waves perhaps twenty times as long as the longest waves that are visible. Our hot-beds are constructed upon this principle. The light-waves pass through the glass freely, but when they appear as heat waves they are imprisoned.

324. **Temperature and Color.**—The radiations given off from a slightly heated body are invisible. As the temperature rises, the vibration frequency of the radiations appears to rise with it. If a platinum wire be gradually heated, by passing an electric current through it, a spectral gray color is emitted at about 400° C., and the wire appears as a dark-red line at 525°. As the temperature continues to rise,

waves of shorter and shorter lengths are constantly added, and the wire appears orange, then yellow, and finally intensely white. We are unable to perceive the colors toward the violet end of the spectrum because they are masked by the longer wave lengths already present. But the colors green, blue, and violet become visible if the longer wave lengths are filtered off by suitable glass.

325. **Röntgen Rays.**—In the year 1895, Professor W. C. Röntgen, of the University of Würzburg, announced his discovery of a new kind of radiation, which he modestly called X-rays, but which are more frequently designated by the name of their discoverer. The rays themselves are invisible, but when allowed to fall upon certain phosphorescent material, such as barium platino-cyanide or calcium tungstate, they cause it to emit rays of such length as to affect the eye. They also have the power to effect chemical changes in a photographic plate. All bodies are transparent to these rays, but in varying degrees. If, for example, we lay a hand upon the holder containing a photographic plate, and let the Röntgen rays fall upon the hand, and then develop the plate, we find that the rays passed through the flesh of the hand more readily than through the bones, and through the bones more readily than through the metal finger ring, as shown by the varying degree to which chemical change

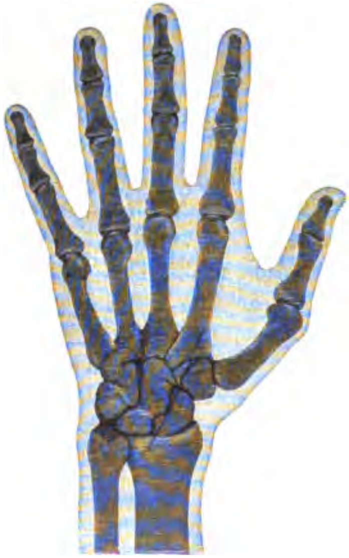

FIG. 237.—Photograph by Röntgen rays.

was effected in the plate underneath these different parts of the hand (Fig. 237). Thus surgeons may locate a foreign body, such as a bullet, in the flesh without probing for it; and thus, too, they may locate abnormal growths, such as internal tumors, etc.

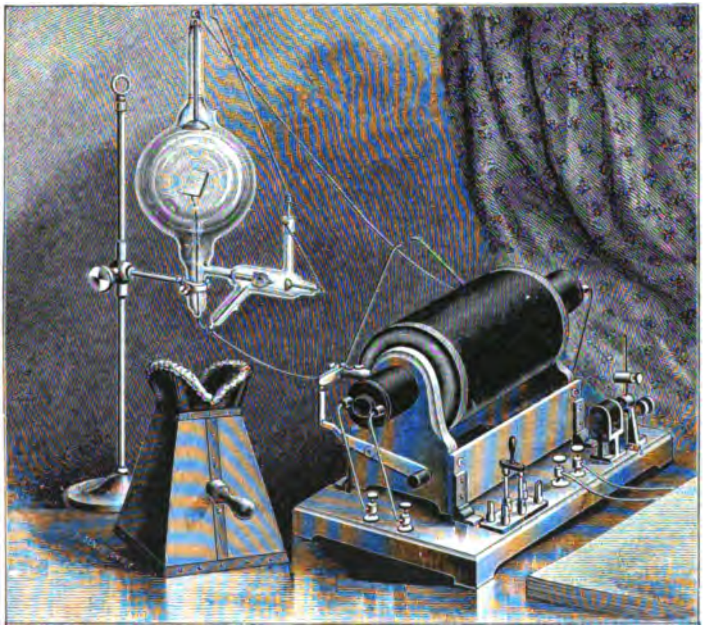

FIG. 238.—Apparatus for Röntgen rays.

The Röntgen rays are produced at the point where kathode rays, which have been discharged into a high vacuum, strike upon a platinum screen or the walls of the vessel in which the discharge takes place. In order to obtain the necessary voltage to drive the electric current through the high vacuum, an induction coil may be used. Fig. 238 shows the vacuum tube, the induction coil, and the fluoroscope, into which the observer looks while holding it turned toward the vacuum tube. The larger end of the fluoroscope has a screen coated with calcium tungstate or barium platino-cyanide, which fluoresces when the Röntgen rays fall upon it.

326. **Herz Waves.**—When a discharge takes place between the knobs of an electrical machine (Fig. 137), or an induction coil (Fig. 186), in addition to the light rays which emanate from the spark, invisible rays pass out in every direction which have wave lengths of several metres. These are sometimes called Herz waves, because of the researches in that field made by a German physicist, Heinrich Herz (1857–1894). Although brick walls are transparent to these waves, they are reflected and refracted by certain other substances. It is with these rays that wireless telegraphy is carried on. By means of suitable receiving instruments, signals have thus been transmitted as far as fifty miles.

CHAPTER XXX

POLARIZATION OF LIGHT

327. **Transverse Vibrations.**—To understand polarization we must go back a moment to the nature of the light waves themselves. While we represent light rays as going out from a luminous body in all directions in perfectly straight lines, the real motion is in a plane at right angles to these rays, and in all possible directions. If we fasten a cord at one end, and, holding the other end in our hand, make the cord ripple in all possible planes, we shall have a rough representation of a real light ray. If the motion of the cord is projected upon the surface to which the end is fastened, we will have a series of radial lines, as shown in Fig. 239, which represents some of the planes in which the ether vibrates. To represent every possible plane of vibration, we should have to turn this circle of radiant lines into a solid black circle. In thinking, then, of a ray of light, we must think of it as vibrating in all possible directions, in a plane at right angles to its line of propagation. When such a ray passes through a homogeneous medium, like the ether, no particular result follows; but when it passes through certain media to be described, we have the interesting phenomena of polarization.

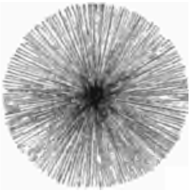

FIG. 239.

328. **Polarization of Light.**—A cord with one end fastened and the other end held in the hand may be rippled in

any and every plane so long as it passes freely through the air. If now it passes through a couple of vertical gratings, the ripples must all be in a vertical plane. Had the gratings been horizontal, only horizontal ripples would have been possible. If one grating be vertical and the other horizontal, no ripples can pass to the end of the cord, for only vertical ripples can pass the second grating; consequently everything stops at the second grating, and beyond that there is no motion (Fig. 240). Something like this appears to happen in certain cases with light, and we call it polarization of light.

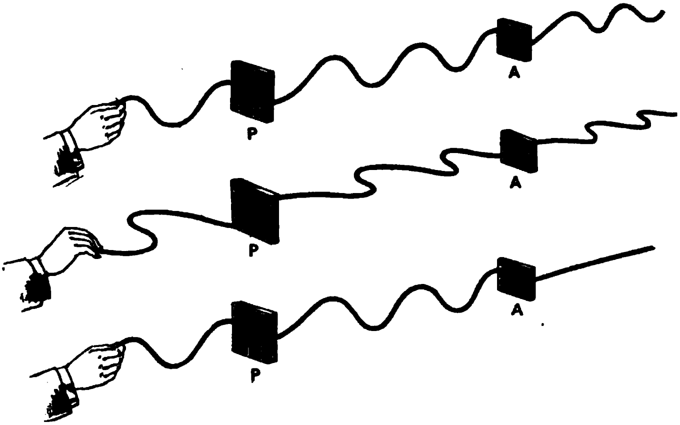

FIG. 240.—Apparatus to illustrate polarization of light.

To illustrate this we may cut two thin slices of tourmaline parallel to the axis of the crystal. These appear to act upon a ray of light as the gratings, represented in Fig. 240, act upon the vibrating cord. When these slices are arranged so that their axes are parallel, as in Fig. 241, *a b*, the ray of light passes through. If they are crossed obliquely, as in *a′ b′*, we have partial extinction of the ray. If they are crossed at right angles, as in *A B*, we have complete extinction of the light. We believe that when the ray of light passes through the first of these slices of tourmaline, all its transverse vibrations are cut off except those parallel to the axis of the crystal. A ray of light which has thus been robbed of all its vibrations except those in one plane is said to be polarized, and the first crystal of tourmaline through which the ray passes is called a polarizer. The second crystal of tourmaline is called an analyzer, because it is by turning this at right angles to the other, and thus extinguishing the light, that we may determine whether or not a ray has been polarized.

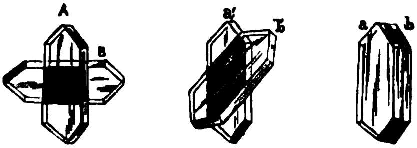

FIG. 241.—Tourmaline polarizers and analyzers.

Light may be polarized by reflection from a plane mirror. It is also polarized by refraction, and various substances, such as Iceland spar or tourmaline, if cut in the proper manner, may serve as analyzers. If a ray of light make with the perpendicular to a mirror an incident angle of about fifty-seven degrees, the reflected ray will be polarized.

329. **Applications of Polarized Light.**—If we arrange a projecting lantern so that we may introduce a polarizer and an analyzer (somewhat separated) between the condensing and converging lenses, we shall be able to exhibit the most interesting and beautiful phenomena of polarized light.

By simply turning the analyzer, we may show the varying degrees of light, from full illumination when polarizer and analyzer are parallel, to complete extinction when they are crossed.

Geologists now study the rocks by making very thin sections, mounting them on glass, and then examining them by means of polarized light. By turning the analyzer we get a beautiful display of changing color. We may, by means of polarized light, test the genuineness of certain gems.

Wonderfully beautiful experiments may be made by dissolving any crystallizable compound, such as salicin or urea, in alcohol, spreading a film of the solution on glass, and introducing the glass, while still wet, between the polarizer and the analyzer. As the solution evaporates, tiny crystals appear on the plate, and with the turning of the analyzer we have the screen covered with a display of rare beauty and variety.

330. **Rotation of the Plane of Polarization.**—It is found that certain substances, such as quartz cut perpendicular to its axis, and certain solutions, such as sugar, when introduced between the polarizer and analyzer, rotate the plane of polarization. The amount the plane of polarization has been rotated is found by turning the analyzer.

In the case of sugar, the angle depends upon the strength of the solution, and this gives us a convenient and accurate method of determining the strength of such solutions.

It was Faraday's great discovery that a wave of polarized light may be rotated by means of a magnet.

331. **The Identity of the Various Forms of Radiation.**—All forms of radiation may be polarized, may be refracted, may be reflected, and may be transformed, the one into the other. We believe that they differ from one another only in wave length, and consequently in the rapidity of vibration. We believe that they are all rays of ether, having transverse vibrations. Those with longest wave lengths and slowest vibrations produce electrical phenomena, those with the next shortest wave length and next fastest vibrations produce heat phenomena, those with the next shortest wave length and next fastest vibrations affect the optic nerve with what we call light, and those with the shortest wave length and fastest vibrations are called chemical or actinic rays, because of their power to effect chemical changes. As might be expected, all ether vibrations tend to effect chemical changes—that is, dissociate the atoms in the molecule; and all ether vibrations tend to effect molecular motion, which is heat.

SOUND

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CHAPTER XXXI

GENERAL PRINCIPLES

332. **Sources.**—All sound-producing instruments must be in a state of rapid vibration. A tuning fork while producing a sound may be shown to be in vibration by touching it to a pith ball suspended by a thread. The ball will bound away as if it had been struck; and truly it has, but so quickly that our eyes can not see the blow. Or, if the prongs of a sounding fork be dipped into water it will throw a spray, and the fork will soon be brought to rest. A sounding bell, if touched with the finger, will instantly cease to produce sound. The long strings of the piano may be seen to vibrate while sounding. A pin or other light object will dance upon the sounding board while the piano is played, and a heavy organ pipe can be felt to be in vibration while producing a sound.

333. **Transmission.**—In order that a sounding body may produce in our ears the sensation of sound, some medium—solid, liquid, or gas—must intervene. If we take the medium away, our sensation of sound ceases, no matter how vigorously the sounding body may keep up its vibrations. If, for example, we put a bell run by clockwork under the receiver of an air pump, and either suspend it by threads, or let it rest on thick wads of cotton or wool, the sound will grow fainter and fainter as the exhaustion proceeds, and will finally cease altogether when a vacuum has been attained. We are justified in believing that the medium is necessary for the transmission of sound, because when we

take the medium away the sound ceases to reach our ears. Experience teaches us that sounds are even more readily transmitted through solids than through gases. If one puts his ear against a long wire or a stick of timber, the scratching of a pin at the other end may be readily heard through the solid when it can not be heard at all through the air. So also liquids transmit sound more readily than gases. The denser the medium the more readily it transmits sound. Also the more elasticity a substance has the more readily does it transmit sound. Fig. 242, representing a number of billiard balls suspended in a row, each an inch or two from its neighbor, may serve to illustrate how sound is transmitted through the air or any other medium. Suppose the ball at one end of the line to be pulled one side and allowed to swing against its neighbor, the second ball will swing over and transmit the blow to the third ball, which will in turn pass on the blow to the next, and so on through the line. If these balls are of ivory or glass, or any elastic substance, the wave will quickly run through the line without much loss; but if the balls are of some inelastic substance, as lead or putty, the impulse rapidly loses force. Thus it is that sound appears to be transmitted through any medium. The sound must be produced by a body in vibration—a column of air, as in the organ pipe and all wind instruments; or a stretched string, as in the piano, violin, harp, and all stringed instruments; or a membrane, as in the drum; or a metallic plate, as in the cymbal, or in fact anything capable of vibration—and these vibrations are transmitted through the air to our ears, which are constructed so as to receive the impression and

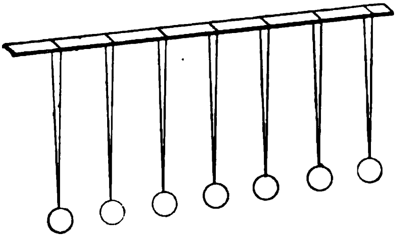


FIG. 242.

translate it into our sensation sound, which is conveyed to the brain by the auditory nerve.

Sounds differ so much that it is hard to realize that they all are the result of the vibration of the air. The air, being a perfectly elastic fluid, and transmitting pressure equally in all directions vibrates from a center outwardly in all directions. Suppose a disturbance to be set up at any one point, as, for instance, by the vibration of a bell (Fig. 243), the sides of the bell in vibration move first in one direction and then in the other, and the air receives the blows of the quivering metal in just the way that the pith ball did from the tuning fork (section 332); and not one blow, but many, up to two or three hundred in a second. Each time then the air receives a blow, it is compressed, and a spherical wave of compression is set up. But between each blow the metal draws back, and consequently sets up a similar spherical wave of rarefaction. A sound wave is spherical in shape, and consists of alternate spherical shells of compressed and rarefied air. There are three respects in which sounds differ: loudness, pitch, and quality.

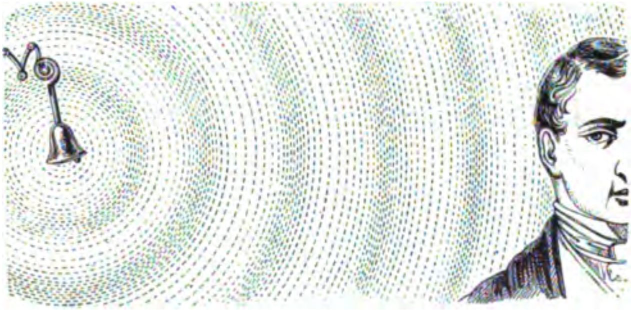


FIG. 243.—Sound waves.

334. **Loudness.**—The harder we strike the tuning fork the louder its sound. If we examine its amplitude of vibration, by dipping it into water, or touching it to a pith ball,

we shall get a correspondingly vigorous fountain or lively blow. It must be that the vibrations of the loud-sounding body are more ample than those of the quieter body. If when the tuning fork is sounding very feebly it is dipped into water, the resulting splash will be found to be correspondingly feeble. Our entire experience leads us to believe that the loudness of a sound depends upon the amplitude of the wave that makes it—that is, upon the degree in which the air is compressed and rarefied.

Re-enforcement.—The tuning fork set vibrating and simply held in the hand produces a very feeble note. To make it audible in a classroom or lecture hall, the fork must be held against some elastic body of larger surface, such as a wooden table top, a door, or an ordinary sounding-board. In this case the larger body is also set into vibration, and the surrounding air is more deeply affected. In most musical instruments we have such an arrangement for re-enforcing the sound, and to give it the volume needed.

Loudness is seldom measured in any strict way. In music it is indicated by some word usually borrowed from the Italian, such as *forte*, loud; *fortissimo*, very loud; *piano*, soft; *pianissimo*, very soft, etc. In physics it is represented, rather than measured, by the amplitude of the wave. The intensity of two sounds may be compared by observing the distance at which they may be heard. The sound wave, being spherical in form, is represented at any instant by the surface of a sphere whose radius is the distance from the sounding body. We know from geometry that the surface of a sphere is equal to $4\pi r^2$. Hence the surface depends on r^2, or the square of the distance. By the principle of virtual velocity, the original energy spread over this larger space must be less intense in exact proportion; so we say that the intensity of any given sound varies *inversely* as the *square* of the distance. There is a slight variation from this, due to the fact that some of the energy of sound is changed to heat.

335. **Pitch.**—The term pitch is used in music and in ordinary speech to indicate the position of a sound in the musical scale. The pitch is high if the note is up toward the treble; the pitch is low if the note is down toward the bass. And this is quite independent of loudness. We all know that women's voices have higher pitch than men's, and children's voices than older people's. However unmusical one may be, one is pretty sure to be aware of the fact that the notes on the right-hand side of the keyboard of a piano or organ are much higher in pitch than the notes on the left-hand side of the keyboard. The idea of pitch in sound is a perfectly definite one. Pitch translated into vibration is equally definite. If two tuning forks of different pitch have a bristle attached to each, and if during vibration each bristle be allowed to trace a line by drawing the fork over smoked glass, it will be found that the tuning fork of higher pitch, the shorter fork, will trace a greater number of waves, giving evidence of being in more rapid vibration than the tuning fork of lower pitch, the longer fork (Fig. 244). We say then that pitch depends upon the number of vibrations per second.

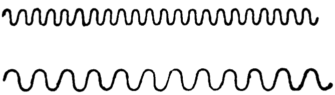


FIG. 244.

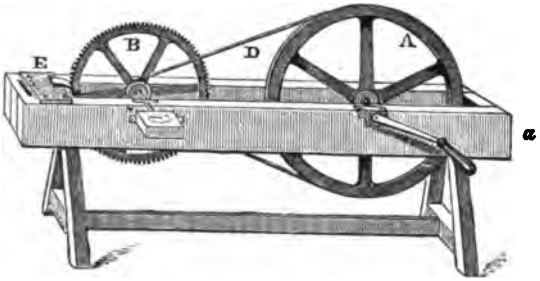


FIG. 245.—Savart's wheel.

We may determine the number of vibrations which correspond to any given pitch by various devices. One is Savart's wheel (Fig. 245), which consists of a large-toothed wheel capable of rotation, and provided with a flexible tongue against which the teeth may strike. The number of teeth, multiplied by the number of turns per second, will give the number of blows the flexible tongue receives, and so the pitch of the resultant note. The faster the wheel turns the higher the note. If, for example, we wish to measure the vibration frequency of a given tuning fork, we have only to set it into vibration, and then rotate the toothed wheel until it gives out the same note. Another simple device is illustrated in Fig. 246. The disk is made to rotate in front of a tube through which a stream of air is passing. Each time a hole in the disk passes the end of the tube a puff of air passes through it. When the disk moves slowly we hear each separate puff; but when the disk moves so rapidly that we may not distinguish the separate puffs, we begin to recognize a tone which rises in pitch as the speed of the disk increases. By attaching to the disk a mechanism similar to that used in the cyclometer of a bicycle, we may, with watch in hand, count the number of revolutions, and from that the number of puffs per second which correspond to a certain pitch of tone. When the tone compares in pitch to the middle C on the piano it is found to have two hundred and fifty-six vibrations per second. Fig. 247 represents an instrument for determining pitch. It works upon the principle just stated, with some modifications in its mechanism. It is known as a siren.

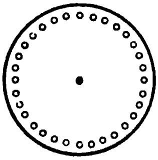


FIG. 246.

336. **Quality or Timbre.**—The Germans call this tone-color. If a note of given pitch be sung by two voices, or sounded by two instruments, say the piano and violin, it will be noticed that there is something distinctive about each note, and we can generally recognize the source of the

note. It can not be a difference in the fundamental tone, as the pitch is the same in all four notes. Yet so real and subtle is it, that it makes one voice or instrument agreeable to our ear, and another voice or instrument disagreeable. Von Helmholtz, the great German physicist, investigated the matter very carefully, and found that this difference in the quality of sound is due to overtones or secondary sound waves that accompany the fundamental or major sound, and give it so characteristic a coloring that no two human voices, and no two instruments, even of the same class and make, ever sound precisely the same note. From a human and æsthetic point of view the quality of a sound is its most valuable character. The tuning fork gives an

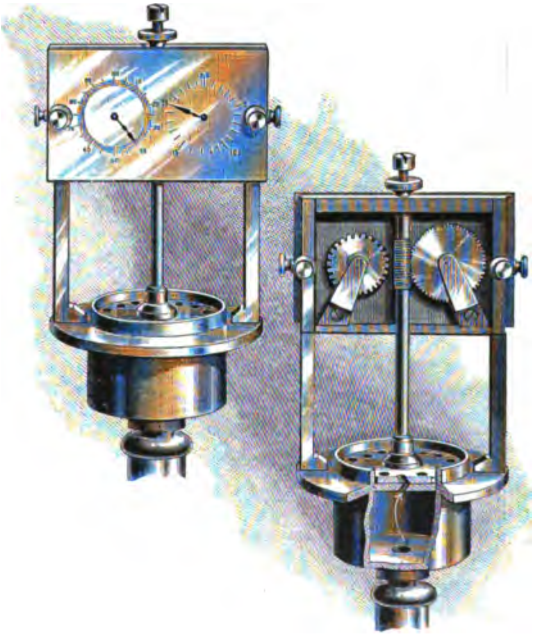


FIG. 247.—Siren.

almost pure note, which, on account of its lack of shading, fails to be acceptable to the ear. Helmholtz was the first to measure the *quality* of a musical note by measuring the accompanying overtones. For this purpose he devised his *resonators* (Fig. 248), hollow globes of thin brass with openings on opposite sides, the smaller one for insertion in the ear, and the larger one for the reception of the sound impulse. The inclosed body of air will vibrate in sympathy with one special note only, and hence serves to detect that note in the midst of many others. By having a series of these resonators it is possible to detect the overtones accompanying any fundamental. This method gives, however, only a partial measure, since the total musical effect depends not alone upon the overtones themselves, but also upon their relative intensity.

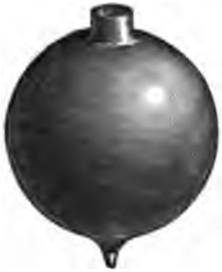


FIG. 248.—Helmholtz resonator.

337. **Reflection, Echoes.**—If we place the chain of ivory balls represented in Fig. 249 so that the last one shall be near to a wall, and then send an impulse along the line by swinging the first ball against the second, this impulse will be reflected back by the last ball striking against the wall and bounding back against its neighbor. In like manner sound waves in the air are reflected by walls of buildings, mountain peaks, etc. This is what we call the echo.

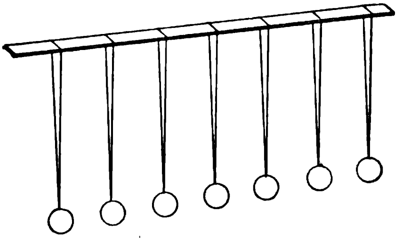


FIG. 249.

338. **Velocity.**—The velocity of sound in air may be determined as follows: Two stations are selected at a known distance apart, and sharp noises, such as the report of a

cannon or gun, are made at either or both stations, and the time that it takes for the sound to reach the other station is carefully noted. The time at which the discharge took place is known to the observer at the second station either by the flash or by an electric signal. Such experiments have been repeated very often and in different parts of the world, and while the results differ slightly, they all give nearly the same result, viz., about eleven hundred feet per second. We may count the seconds between the lightning flash and the sound of the thunder and calculate our distance from the thunder cloud. We may see the steam pouring from the whistle of a distant steamship, and by counting the seconds before the sound is heard calculate its distance.

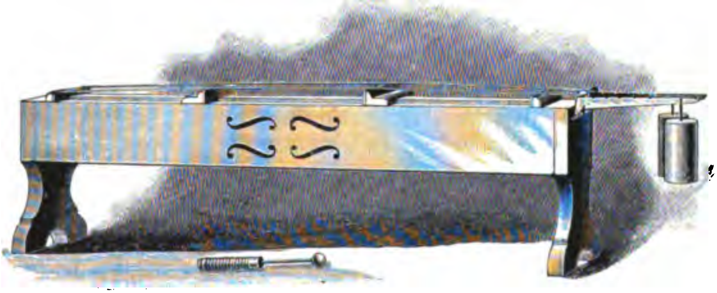


FIG. 250.—Sonometer.

It is evident that loudness, pitch, or quality have no effect upon velocity; for when we hear a band of musicians playing at a distance the loud tones and the soft tones, the tones of high pitch and low pitch, and the tones of various quality, if played simultaneously, all reach the ear together.

339. **Vibration of Strings.**—A useful and standard instrument for examining the vibrations of strings is the *sonometer*, or *monochord* (Fig. 250). A stretched string, capable of vibrating under varying tensions and lengths,

and capable of being replaced by other strings, is re-enforced by a sounding box made of dry, elastic wood. By means of this instrument the following laws may be illustrated and verified:

1. Pitch varies with the material of the string.
2. Pitch varies inversely with the length.
3. Pitch varies inversely with the diameter.
4. Pitch varies with the square root of the tension.

We may sum this up by saying that strings which are heavy, long, thick, and slack, give a low note, while strings which are light, short, thin, and tense, give a high note.

In the piano the strings are tightly stretched—steel wire for the treble, and steel wire wrapped around with copper for the bass. The keyboard is fixed, and when a key is struck the blow is transmitted by means of levers and hammers to the corresponding string. The wires are stretched between iron pins fastened to the frame of the instrument. The length of the wire is determined by the position of the agraffe, or bridge, which rests directly upon the large spruce sounding-board that forms the bottom of the piano box. The instrument is tuned by turning the pins and so changing the tension of the strings. The position of the hammers is a matter of great importance, since the blow on the strings determines the overtones. In most pianos the strings are struck at a distance of one seventh, one eighth, or one ninth from the end, so as to bring out the desirable overtones. Different pianos differ in sweetness and tone largely because of their overtones and the greater or less efficiency of their sounding-boards.

A modern grand piano, such as the Steinway, contains forty thousand separate pieces of material. The piano, in spite of many musical defects, is a singularly rich instrument, since it offers such large opportunities for the play of harmony. Not only may several notes be struck at once in a given chord, but the combination of two parts—the bass and treble—allows added richness and variety.

In other stringed instruments, such as the violin and violoncello, the vibrations are induced by means of a rosined bow, and the sound is re-enforced by a box beneath the strings, a box which is of all forms for acoustical re-enforcement the most perfect in design. The much-prized instruments of Stradivarius, Amati, and Guarnerius, owe their value to their perfect form, to the elasticity of their well-seasoned wood and marvelous varnish, and, some persons think, to the fact that several subsequent generations of master violinists have induced in them the "habit" of harmonic vibration. Musically, the violin is much superior to the piano; the single notes are far richer by reason of the full set of harmonics present, and particularly of the higher harmonics.

340. **Sympathetic Vibrations.**—The richness of the organ, piano, and other musical instruments is due not only to the overtones accompanying the fundamental note, but also to a second group of accompanying notes due to what is called sympathetic vibration. If two tuning forks of the same pitch, and mounted on suitable resonator boxes be placed near each other and one of them set in vibration, it can readily be shown that the second untouched fork is also vibrating. A pith ball brought in contact with the fork will be thrown aside; or, if the original fork be silenced, the second fork will be found emitting an unmistakable note. Had the forks been of different pitch, no such sympathetic reaction would have taken place. Similarly, if the loud pedal be pressed down, and a strong, pure note be sung into a piano, the string corresponding to that note will be set into vibration.

CHAPTER XXXII

MUSIC

341. **Music and Noise.**—We know the sensation differences between music and noise. The one pleases by its regularity and rhythm and by a certain anticipatory quality which leads us to expect a given effect, and then gratifies our sense of anticipation by giving us the effect. The other displeases us, and the more so the more sensitive our organization. It displeases by its irregularity. It must be said, however, that the line between music and noise is not a hard-and-fast one, even to musicians. There are certain passages in the compositions of Wagner and of the more stormy Russian artists which are music to one school of musicians and noise to another school. However, we all of us know in general the sensation differences between music and noise. A vibrating tuning fork gives an undoubted musical note of very pure quality, while a door slammed gives a decided noise. The tuning fork vibrates regularly, giving so many perfect waves per second, and, as we have seen, traces an even, symmetrical line on smoked glass. If a visiting card is drawn slowly over the teeth of a saw we hear the successive taps or noises of the card striking against the teeth of the saw; but if the card is moved very rapidly, so that we may no longer recognize the distinct taps, the noise begins to assume the character of a tone. So it is with the puffs of the siren (335); so it is also with the sound of a buzz saw.

342. **The Musical Scale.**—All nations have made such a selection of musical notes, and have framed them into a

series known as the musical scale. This has varied greatly in historic times, and even now we may not regard it as quite fixed. The Greeks had what seems to us now a very meager and almost unmusical scale. It was, however, carefully thought out, and has practically formed the basis of all modern music. The scale was greatly enriched during the middle ages, and particularly when music came into such large service in the Church. The sacred music of mediæval times, especially in Italy and Germany, made great and rapid advance toward modern perfection. All this work, however, was purely art work, and not as yet science. The musical scale that has thus come down to us is a product of the rich, emotional, and æsthetic life of the world, and not of its thought. The older musicians knew nothing of acoustics, knew nothing of vibration numbers, and sound waves. They knew only what pleased the heart and expressed its reverence and delight.

343. **The Octave.**—Pitch depends solely upon the number of vibrations per second; but as soon as we begin to compare notes of definite pitch with one another we are struck with the fact that when we have gone a certain distance in either direction the notes appear to be repeating themselves. They are higher or lower, it is true, but they have the same musical character. A corresponding relation is found to exist between their vibration frequencies. Taking the note C, making 256 vibrations per second, it is found that the next note above it, C^{I}, that has the same musical character, makes 512 vibrations, or just *twice* as many as C. Above that the next similar note is C^{II}, with 1,024 vibrations. Then comes C^{III} with 2,048 and C^{IV} with

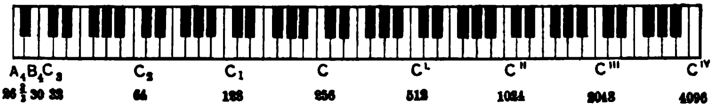


FIG. 251.—The piano keyboard.

4,096 vibrations, and we reach the upper limit of the piano. Had we gone down instead of up, we should have found the first lower note similar to C to be C_1, making just *half* the number of vibrations, or 128. Below that comes C_2, with 64 vibrations, and still below that C_3, very far down among the thunderous notes of the bass, and making only 32 vibrations per second. This is very near the lower limit of musical sound. C_3 to C^{IV} covers about the range of an ordinary piano keyboard (Fig. 251). Between C and C^{I} custom has introduced six notes, and we designate them by the letters of the alphabet—D, E, F, G, A, B. The scale thus repeats itself every seven notes. This group of eight notes is called the octave. C^{II} is two octaves above C; C^{IV} is four octaves. Similarly, C_3 is three octaves below C. The scale may begin on any note of the octave, but it will be best to regard the scale beginning with C as a type.

344. **Vibration Ratios of the Musical Scale.**—If we take the number of vibrations of the fundamental note of the scale as unity, then its octave will be 2, and the intervening notes as follows:

C	D	E	F	G	A	B	C′	(1)
do	re	mi	fa	sol	la	si	do	(2)
1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2	(3)
256	288	320	341⅓	384	426⅔	480	512	(4)

(1) is the usual musical notation; (2) is the notation commonly used in singing; (3) is the vibration ratios which hold for the scale whatever its position on the keyboard; and (4) is the working out of these ratios for the octave, beginning with the middle C.

Intervals.—When we look closely at such a scale we see that the intervals are not all equal. The intervals between *mi* and *fa* and between *si* and *do* are called half tones, and the other intervals are called whole tones, although the "whole tones" are not equal to each other, nor are the so-called half tones half of any one of them. On the piano keyboard each of the so-called whole tones are divided into halves by the black keys (see Fig. 252). This enables one to

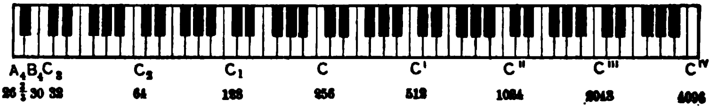
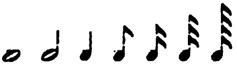
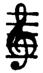
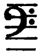


FIG. 252.—Piano keyboard.

begin with *do* on any letter and bring in the half step between *mi* and *fa*.

345. **Musical Score.**—It is the custom to represent musical notes by conventional signs—  which are read whole note, half note, quarter note, eighth, sixteenth, thirty-second, and sixty-fourth. These terms apply, not to the tone intervals, but solely to the time to be given to each tone. Five parallel lines constitute the staff on which the notes are to be placed, and the position of the notes on the staff indicates their pitch. When the staff will not accommodate all the score, additional lines, called ledger lines, are employed. In music written for two hands, as the score for piano and organ, separate conventions are used; for the right hand the treble clef,  and for the left hand the bass clef,  Fig. 253 represents the position of the letters upon the score.

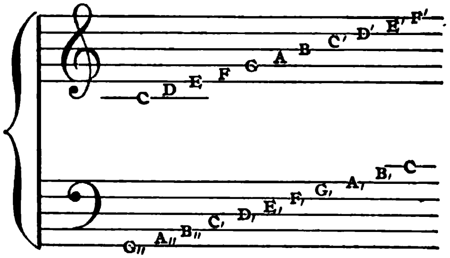


FIG. 253.

346. **Melody.**—The art of musical composition is perhaps the supreme act of which the human mind is capable.

The earliest composition was naturally the simple arrangement of sounds in pleasing succession, and for this sequence of sound the term *melody* has long been used. The arrangement and the effect are both simple; one sound is followed by another according to no perceived physical law, but solely, perhaps, in accordance with some æsthetic law by which the succession gives us pleasure. Some of our most touching music, our folk songs, ballads, and the like, are pure melody. So, in more complicated music, melody is sometimes introduced by way of contrast or relief, or to emphasize, by its very simplicity, a leading thought in the composition. Wagner nearly always introduces the characters in his operas by such a melody, or "Leit-motif." A simple melody is often used as the theme or text out of which more elaborate music is to be developed. The above example of very beautiful melody is the theme of the slow movement of Beethoven's Fifth Symphony (Fig. 254).

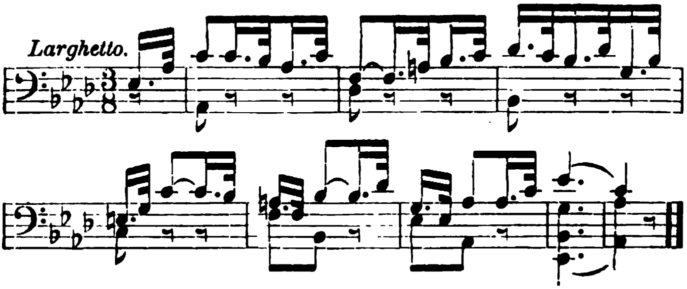


FIG. 254.—Theme from Beethoven's Fifth Symphony.

347. **Chords.**—Melody is simplicity itself, for, while it may please in greater or less degree, it can never absolutely displease, because it can never be other than musical. But the possibilities of music would be ill explored if we confined ourselves to a mere succession of musical sounds, however agreeable they might be. There are tremendously greater possibilities when we come to sound several notes at the same time. Two or more notes sounded simultane-

ously constitute a *chord.* If the effect is agreeable, we call it concord; if disagreeable, discord.

The simplest chords contain but two notes, as the octave, C C′; the perfect fifth, C G; the fourth, C F; the major third, C E; the major sixth, C A, and the less agreeable minor third, minor sixth, etc. These binary combinations form the basis of our musical analysis, since chords of three or more notes may be resolved into their binary chords.

The most important chord in music is the *major triad*, C E G, or *common chord*, which may be considered as made up of a major third, C E; a minor third, E G; and a perfect fifth, C G. By substituting C′ for C, we get the *chord of the sixth*, E G C′; and by the further substitution of E′ for E, we get the *chord of the sixth and fourth*, G C′ E′. These three chords are all agreeable, but produce somewhat different musical sensations.

Harmonics.—The quality of a musical note depends, as we have seen, upon the overtones. The upper harmonics are too faint to be appreciable, but the lower ones are very important. When we strike C, we have the following succession of notes:

C	C′	G′	C″	E″	G″,	etc.
1	2	3	4	5	6,	etc. (vibration ratios).

We may discard all above G″, and represent it thus (Fig. 255): In the harmonics of this one note we have already present the principal chord of music, the octave, C C′; the perfect fifth, C′ G′; the fourth, G′ C″; the major third, C″ E″; the minor third, E″ G″. This may account for the fact that these chords are agreeable, since they merely emphasize notes already present in the fundamental. In general, notes to be harmonious must have vibration frequencies that stand to each other in a simple ratio. There is, however, conflict between the series of harmonics.

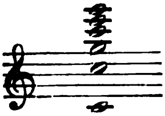


FIG. 255.

348. **Harmony.**—The highest expression of musical art is in *harmony,* which is the combining of many sounds into one agreeable composition. It is practically a progression of chords, groups of notes sounded in such orderly succession as to produce the impression of unity and purpose. The laws of harmony are very intricate, and presuppose an acquaintance with elementary music. The above bars from Schumann's Nachtstück are a beautiful illustration of harmony (Fig. 256).

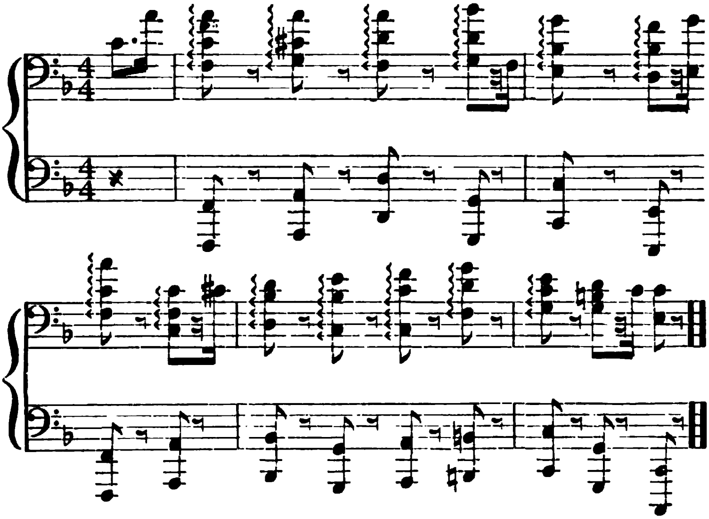


FIG. 256.—Illustration of harmony from Schumann's Nachtstück, No. 4.

349. **Counterpoint.**—As harmony is the highest expression of music, so counterpoint is the highest expression of harmony. In counterpoint we have harmony brought about by the combination of two or more melodies, a combination which yields the fullness and satisfaction of harmony with the movement and life of melody. The great master of counterpoint was Sebastian Bach (1685–1750). The accompanying excerpt from Palestrina illustrates counterpoint

WOLFGANG AMADEUS MOZART (1756-1791).

One of the greatest musicians the world has produced. While a mere lad he played before nearly all the sovereigns of Europe. "His music from the first to the last has been most highly appreciated."

(Fig. 257). Handel, in England, and other masters of the seventeenth and eighteenth centuries brought counterpoint to a perfection that it has never since reattained. It occupies, indeed, a very subordinate part in the compositions of the nineteenth century, which are mainly engaged in exploiting the possibilities of harmony. But as harmony grew out of counterpoint, so it now seems probable that a more magnificent counterpoint will grow out of our enlarged knowledge of harmony. The tendency to return to coun-

From Palestrina.

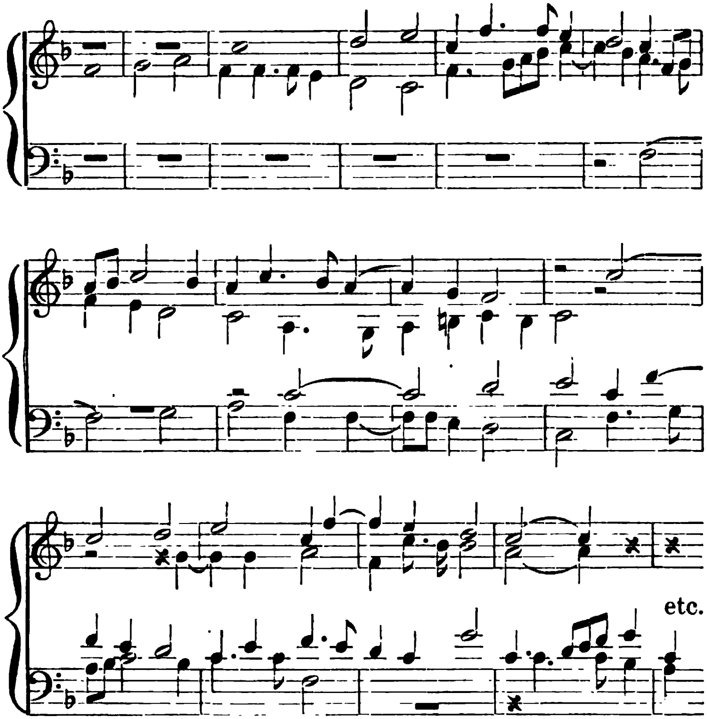


Fig. 257.—Illustration of counterpoint.

terpoint is shown in the work of such modern composers as Mozart and Mendelssohn.

It has been well said that melody gives one the idea of *motion*, and harmony the feeling of *rest*. Melody must progress, or it ceases to be melody, but a simple harmonious chord is complete and perfect in itself. In modern counterpoint we have the strength of both, the movement of the contrasted melodies and the restful background of their underlying harmony.

Our ideas of musical beauty are so variable that it seems impossible to reduce them to strict physical statement. Taste changes, and each new master gives greater flexibility to the material of music. To the complaint that one of his works contained a certain passage that was not allowed, Beethoven replied: "Then *I allow it;* let that be its justification."

350. **Reading Music.**—It might well be a part of every liberal education to learn to read music intelligently. There are people who read music so easily, and construct it in their minds so vividly, that they get as great pleasure in simply turning over the leaves of a musical composition as we do in glancing over a favorite poet.

CHAPTER XXXIII

MISCELLANEOUS APPLICATIONS

351. **Speaking.**—The opening between the vocal cords is called the *glottis*, and is practically a slit, somewhat like the lip of an organ pipe. When no sound is produced, the vocal cords are far apart, and the glottis takes the shape of a V, with the wide part behind. When voice is produced, the vocal cords are drawn together under some tension, their edges are parallel, and the glottis becomes a mere narrow slit (Fig. 258). The pitch of the emitted sound depends on the tension of the vocal cords. As this is controlled by the muscles of the larynx, we can alter the pitch of our voice at will, but only, of course, within somewhat narrow range.

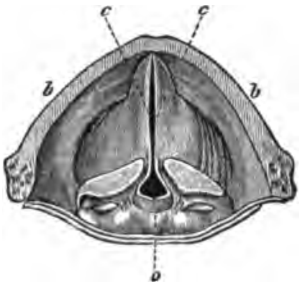


FIG. 258.

The character of the voice depends on small structural differences in the larynx. In women and in boys the voice is higher, simply because the vocal cords are shorter, and hence vibrate a greater number of times per second. In the same way, soprano and alto voices in women, and tenor and bass voices in men, result from the size and tension of the vocal cords. A trained singer, by altering the tension of the cords, can cultivate great flexibility. This control, like the control of nearly all our faculties, is best acquired when we are young.

This accounts, however, only for the voice itself, and not at all for speech. The animals have a very similar apparatus for producing sound, and, in the case of the birds, they use it very skillfully.

In speech the voice has to have a very definite character, and many modifications, in order to express all our varying shades of meaning. The primary speech sounds, vowels and consonants, are brought about by changing the shape of the cavity of the mouth, an operation depending mainly on the tongue and lips. This change in the quality of the tone is due, physically speaking, to the overtones which are produced by the varying form of the mouth. The character of the sounds, as elements of speech, is quite independent of the tension of the vocal cords.

The human voice only covers a range of about two octaves. Few people in ordinary speech cover one octave. The rising inflection at the end of a question sometimes amounts to a fourth; the falling inflection at the end of a simple sentence to a fifth, and even emphasis, where produced by a change of pitch, seldom exceeds a fifth. The cultivation of a greater range would add much to our power of expression.

In singing, the sound itself is the great thing, and the words quite secondary. The great operas are sung in Italian, because of the greater wealth of vowel sounds in that language. In some modern music no words are used at all. A simple vowel sound is selected, and the musical effect gained by variations of pitch and time. In this case, the voice is treated as a simple musical instrument, and not at all as an organ of speech. The physical process of singing depends for its success mainly on the flexibility and control of the vocal cords, and upon the ability to produce a sustained and uniform blast of air through the glottis. In the best systems of modern voice culture, this flexibility is the main thing sought for, and the "singing voice," as it is well called, is cultivated both for speech and song.

In compass, the human voice ranges from about F_2 in the bass (86 vibrations) to about F^1 in the treble (768 vibrations). Exceptional soprano voices have gone as high as E^{11} (1,280 vibrations). One voice is seldom able to cover more than two octaves.

352. **Hearing** is physiologically the reverse process of speaking. Speech begins in the brain as a thought, passes to the muscles of the larynx, tongue, and lips as a nerve impulse, and emerges into space as an air vibration. Hearing, on the contrary, depends for its stimulus upon an air vibration, which is transmitted by the ear as a sensory impulse, and ends in the brain with thought. Hearing, therefore, consists of three distinct processes—excitation, transmission, and interpretation. The excitation consists in a sound wave impinging on the drum of the ear. The sound wave is usually of the air, but it may also be of the water, if we put our ear beneath the surface. The excitation may also be produced by direct contact with a vibrating solid body, as when a sounding fork is held against the bridge of the nose, or against the teeth. But in general the excitation is aërial, and strikes the ear drum. Here a whole series of wonderful things happen. The ear drum is a stretched membrane, very thin and very strong. It will bear the pressure of a column of mercury fifteen inches high—that is, the pressure of half an atmosphere. This ear drum or membrane separates the outer ear from the drum cavity. In this there are three small and delicately poised bones which receive the vibrations of the ear drum, and pass them on to the inner ear, and so, by means of the auditory nerve, to the brain itself.

The act of transmission is a very complicated one, involving as it does so many distinct physiological parts—the external ear, the external auditory canal, the drum membrane, the middle ear with its three tiny bones, and the ventilating canal that leads to the back of the mouth; the Eustachian tube; the internal ear with its wonderful canals and processes; and finally the auditory nerve going directly to the temporal lobes of the brain.

But even more wonderful than this process of transmission is the interpretation of the nerve impulse into significant sound, when it reaches the brain, and about this we know absolutely nothing at all.

353. **Limits of Sound.**—As a sensation, sound is limited. The human ear will not respond to those which have more than 40,000 vibrations per second. Many persons can hear nothing above about 12,000 vibrations, and consequently do not detect the squeal of a mouse or the cry of a bat. We are all deaf to many of the shrill sounds of the insect world. Some animals are believed to be able to hear sounds that quite escape our own ears.

Music employs only the lower notes, from about A_4 ($27\frac{1}{2}$ vibrations) to C^{IV} (4,224 vibrations) on the piano, and up to D^{IV} (4,752 vibrations) on the piccolo. The middle C is counted at 256.

354. **The Phonograph.**—No scientific instrument in its day has excited greater interest than Mr. Thomas A. Edison's phonograph, or sound-recording apparatus, invented in 1878, and first apprehended as a scientific toy, but since brought forward as a serious servant in the affairs of everyday life. The phonograph consists in a horizontal axle capable both of rotation and of longitudinal advance. On this is mounted a cylinder, covered in the early days with tin foil, but now made with some plastic composition for its surface. A fixed mouthpiece is mounted over one end of the cylinder, when the axle is at its extreme position. The mouthpiece has a flexible diaphragm, provided at the center of its rear face with a small, sharp stylus, which presses against the plastic surface of the cylinder.

When talking into the machine the cylinder rotates, and also slowly advances, so that a fresh portion of its surface is constantly passing under the stylus. Imagine the mouthpiece in position, and the cylinder slowly rotating.

SIR WILLIAM THOMSON (1824–).

(LORD KELVIN.)

Any sound waves striking against the diaphragm set it into vibration, and the little stylus no longer traces an even groove on the surface of the cylinder, but a groove which is now of varying and constantly changing depth. Every sound is thus recorded in these minute characters on the surface of the cylinder, and may be reproduced by throwing back the mouthpiece, bringing the cylinder back to its original position, adding a suitable speaking trumpet to the mouthpiece, and then repeating the motion of the cylinder. The little stylus, passing over its own tracing, moves in and out with the varying depth of the groove, and so produces in the diaphragm vibrations similar to those originally induced in it. The trumpet strengthens these sound waves, and we have a reproduction of the speech or music curiously like and curiously unlike the original.

Uses of the Phonograph.—It was hoped that the phonograph might be used in place of dictation, both by editors and busy letter writers, the cylinder being sent at once to the printing office, or mailed to the correspondent at the other end, but this practical use of the phonograph has not yet been realized. It remains chiefly as an amusement for the curious in our big cities and popular resorts.

A much more important use than this would be the application of the phonograph to the reproduction of books, so that the blind could be read to, and all of us, tired perhaps with the day's work, and willing to save our eyes of an evening, could hear our favorite author read. When we went to buy such books, the shopkeepers would ask us, not whether we preferred the Avon edition, or the Riverside, or the half calf or morocco, but simply whether we preferred Mrs. Scott Siddons's rendition, or Mr. Horace Howard Furness's, or Mr. Robertson's, or some other good reader's.

355. **The Telephone** means sound at a distance, and is one of the most important of modern sound instruments. The *acoustic* telephone is only a box, but its principle is

worth considering. The transmitter and receiver are alike simply a little cylinder of wood or metal having one end open and the other end closed by parchment or other flexible diaphragm. A fine wire or string leads from the center of the diaphragm of one instrument to the center of the diaphragm of the other. The wire or string must pass freely from one instrument to the other, and must be moderately taut. When you speak into one cylinder, the transmitter, the diaphragm is set into vibration, and these vibrations produce corresponding longitudinal vibrations in the wire or string, and so in turn are transmitted to the diaphragm of the receiver. Here they produce vibrations of the air similar to the original sound waves. If the receiver be held to the ear, the message is distinctly heard over a distance of several hundred feet.

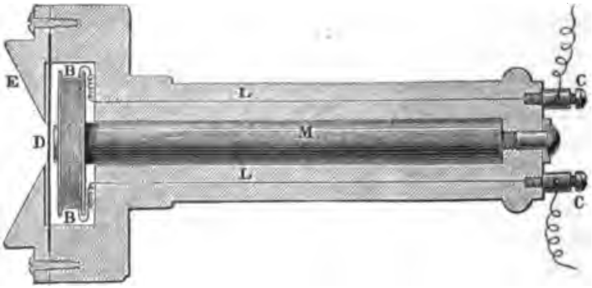


FIG. 259.—Telephone receiver.

The *magneto*-telephone depends upon both acoustical and electrical principles, but with a little care may be readily understood. Remove the top of a regular telephone receiver and examine its construction, or else consult the accompanying figure (259). There is a flexible diaphragm or disk, *D*, made of thin iron, and directly back of this disk a steel bar magnet, running the length of the instrument. The end of the magnet nearest to the disk is surrounded by a coil of fine insulated copper wire, *B*, whose ends are connected with the binding posts, *C*, on the far end of the telephone receiver, and through those with the line wire. This instrument may serve either as transmitter or receiver, though it is now only used in practice as a receiver. When you speak into the telephone, the iron diaphragm is set into vibration, and currents of electricity are induced in the coil of copper wire (Fig. 259). The direction of these currents varies with the approach and recession of the diaphragm, and produces variations in the strength of the magnets at each end of the lines. These variations set up corresponding vibrations in the diaphragm of the receiver at the farther end of the line; the air is thrown into corresponding vibrations, and so brings the sound to the ear. The acoustic principle of the Bell telephone is very similar to that of the acoustic telephone, except that the vibrations are transmitted not directly as a pulsation of the string, but indirectly as a varying current in the wire. The electricity simply acts as the carrier of the energy. In the transmitter the sound energy is transformed into electric energy, and this, in the receiver, is retransformed into sound energy. Such a telephone is in reality a magneto-electric machine. For this and the modern form of the telephone see sections 266 and 268.

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THE END

TWENTIETH CENTURY TEXT-BOOKS

PHYSICAL EXPERIMENTS

A LABORATORY MANUAL

BY

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PROPERTIES OF MATTER AND MECHANICS OF SOLIDS

- I. Extension and Weight of Matter.
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- II. Properties of Matter.
  - 1. *Cohesion and Adhesion.*
    - Experiment 6.
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    - Experiments 7 and 8.
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- III. Mechanics of Solids.
  - *The Pendulum.*
    - Experiments 26, 27, 28, 29. Exercise 30.
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    - Experiments 34, 35. Exercises 36–57. Figs. 4–28.
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I. EXTENSION AND WEIGHT OF MATTER

Exercise 1.—To determine the ratio between an inch and a centimeter.* Measure the line (Fig. 1) in inches to the hundredth part, and in centimeters to the quarter of a millimeter.

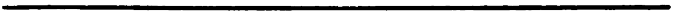

Fig. 1.

Express the result decimally and in the following form :

.... in. = ... cm.

From this result calculate results for the following :

(a) 1 in. = .. cm.
(b) .. in. = 1 cm.
(c) .. in. = 100 cm. (1 meter).

Exercise 2.—To determine the ratio between a meter and an inch. Measure the given line (to be supplied in the laboratory) in meters and in inches. Express the result as follows :

.... m = ... in.

Calculate results for the following :

(a) 1 m. = .. in.
(b) .. cm. = 1 in.
(c) 1 cm. = .. in.

Compare these results with those obtained in the former exercise. Which are probably more nearly correct ? Why?

---

* Always draw along the edge of the ruler on which there is no scale. In making measurements turn the ruler upon edge, so that the scale touches the paper.

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Exercise 3.—To determine the ratio between an ounce and a gram. Place an ounce weight or some multiple of an ounce upon the scale pan. Balance it by gram weights to the tenth part of a gram. Express the result as follows:

.... oz. = ... gm.

Calculate the results for the following:

(a) 1 oz. = ... gm.
(b) .. oz. = 1 gm.
(c) 1 lb. = ... gm.
(d) .. lb. = 1 kg. (1,000 gms.).

Exercise 4.—To determine the ratio between a quart and a liter. Measure a quart, pint, or half pint of water, and find how many cubic centimeters it is equal to. Express the result as follows:

.... qt. = ... c. c.

Calculate the following:

(a) 1 qt. = ... c. c.
(b) .. qt. = 1,000 c. c. (1 liter).

Exercise 5.—To determine the weight of a cubic centimeter of water in grams. Place a measuring glass upon the scales and balance it. Pour in water to any depth, weigh the water in grams, and read the volume in cubic centimeters. Add more water. Read the volume and add weights to restore the balance. Repeat several times. Express the results as follows:

First trial .... c. c. of water weigh .. gm.
Second trial .... c. c. of water weigh .. gm.
Third trial .... c. c. of water weigh .. gm.
Total .... c. c. of water weigh .. gm.

Calculate the following:

(a) 1 c. c. of water weighs .. gm.
(b) 1 liter of water weighs .. gm.

II. PROPERTIES OF MATTER

1. Cohesion and Adhesion.

Experiment 6.—Wet two plates of glass and press them together. Pull them apart again. Try to keep their faces parallel while doing so. Touch one of them to the surface of water. Lift it from the water. Try to keep its face parallel to the surface of the water while doing so. Try other liquids, such as mercury, oil, etc. Discuss this experiment rather fully.

Is it generally easier to separate the liquid from the solid, or the liquid from the liquid?

Gluing and cementing.
Welding of metals. Soldering.
Solid, liquid, and gaseous state of matter.

2. Porosity.

Experiment 7.—Put water into a test-tube to the depth of about an inch. Then slowly add about an inch of alcohol. Measure the height of liquid in the test-tube. Shake them well together and measure again. Explain.

Experiment 8.—Hold a piece of blackboard crayon under water. Why do air bubbles rise to the surface?

Wood, sponge, leather, pumice stone.

3. Capillarity.

Draw out some glass tubing into capillary tubes of various sizes.

EXPERIMENT 9.—Put them into cold water; into hot water; into alcohol; into mercury. How is capillarity affected by the size of the tube, by temperature, and by the kind of liquid used?

EXERCISE 10.—Explain the appearance of the surface of water in a U-tube three sixteenths of an inch in diameter. Explain the appearance of the surface of mercury in the same tube.

Candles and lamp wicks.
Blotting paper.
Sponges.
Loaf sugar.

4. Diffusion of Liquids.

EXPERIMENT 11.—Invert a test-tube filled with water in a small tumbler containing copper sulphate. Allow it to stand several days.

5. Diffusion of Gases.

EXPERIMENT 12.—Invert a wide-mouthed bottle of hydrogen over one of oxygen. After they have stood for several minutes bring a flame to the mouth of each. Explain.

Nitrogen is lighter than oxygen. Why are they not in layers in the atmosphere?

6. Osmose.

EXPERIMENT 13.—Put a concentrated sugar solution into a test-tube to the depth of about two inches. Tie a piece of gold-beater's skin over the mouth, and invert it in a small tumbler of water. Crack a hole in the upper end of the test-tube. Allow the apparatus to stand for several days, and notice what happens.

EXPERIMENT 14.—Tie gold-beater's skin over the bottom of an Argand lamp chimney. Fill the chimney with concentrated copper-sulphate solution as far as the constriction. Support the chimney to this depth in a tumbler of water. In which direction is the greater flow?

Rising of sap in trees.

7. Crystallization.

EXPERIMENT 15.—Fill a test-tube half full of ammonium chloride. Add water so that the tube shall be about two thirds full, heat until the ammonium chloride is dissolved. Allow the solution to cool slowly, and watch the crystals form.

EXPERIMENT 16.—Dissolve 50 grams of alum in 50 grams of hot water. Examine the crystals which form on cooling.

EXPERIMENT 17.—Make a saturated solution of copper sulphate. Allow the solution to cool, and examine the crystals.

EXPERIMENT 18.—Heat some small pieces of roll brimstone until they have melted to a straw-colored liquid. Examine the crystals which form on cooling.

EXPERIMENT 19.—Dissolve some flower of sulphur in a little carbon bisulphide. Cover the solution and set it aside to evaporate, and compare the sulphur crystals obtained by this method with those obtained by melting the sulphur.

EXPERIMENT 20.—Fill a one-ounce narrow-mouthed bottle with water, cork it, and surround it with a freezing mixture of salt and ice. Allow it to stand fifteen or twenty minutes, until the bottle cracks. Uncover carefully to see what has happened to the cork.

Crystallization of water, type metal, etc.

8. **Viscosity.**

EXPERIMENT 21.—Melt some small pieces of roll brimstone in a test-tube. Then gradually raise the temperature of the melted sulphur to such a point that the test-tube may be inverted.

EXPERIMENT 22.—Support a stick of sealing wax or a paraffin candle at either end in a horizontal position, and leave it for several weeks or months until it becomes permanently bent.

Perfect rigidity, viscosity, perfect mobility.
Balsam, molasses, honey, pitch, asphalt, concrete walks.

9. **Elasticity.**

EXPERIMENT 23.—Measure a piece of elastic. Stretch and release, then measure again. Repeat several times. What is meant by perfect elasticity?

EXPERIMENT 24.—Draw a piece of glass rod out into fine threads. Notice their elasticity upon bending.

Elastic force of gases.
Tempered steel.
Steel springs.
Spring balances.

10. **Malleability.**

EXPERIMENT 25.—Pound a piece of lead into a thin sheet. Flatten melted glass by pressing it between forceps.

Gold leaf.

III. MECHANICS OF SOLIDS

The Pendulum.

EXPERIMENT 26.—Determine whether time of vibration is independent of length of arc (amplitude of vibration).

Use a pendulum (a wooden or glass ball attached to a thread is convenient) about 18 inches long,* and count the number of swings it makes in a minute through arcs of various lengths.

EXPERIMENT 27.—Determine whether time of vibration is independent of the weight of the ball. Use balls of various sizes and weights.

EXPERIMENT 28.—Determine the length of a pendulum that will swing 60 times a minute. Begin with one about 1 meter long.

EXPERIMENT 29.—Determine how the length of the pendulum is related to the time of vibration. Start with a pendulum about 24 inches long. Count the number of swings it makes in a minute. Make it 6 inches long, and record as before.

What are the laws governing the pendulum?

EXERCISE 30.—Determine the height of the ceiling of your laboratory by counting (per minute) the number of swings of a pendulum suspended from there. Add to the result which you obtain the height of the middle of the ball from the floor.

The metronome, clocks.

---

* The length should be measured from the *middle* of the ball.

Second Law of Motion.

EXPERIMENT 31.—Determine by means of the apparatus represented in Fig. 2 whether an object projected horizontally will reach the floor in the same time as one let fall vertically from the same height.

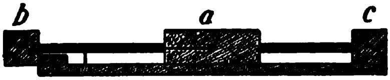

FIG. 2.—Apparatus for illustrating second law of motion.

Fig. 2 represents a thin strip of wood to which is fastened a small block (*a*). Through this block passes a dowel rod as long as the strip. *b* and *c* represent two blocks, through one of which (*b*) a hole is bored to fit the dowel rod. By means of rubber bands the dowel rod sets both blocks free to fall at the same instant, but projects one horizontally and the other vertically.

Inertia.
Stable, indifferent, and unstable equilibrium.
Gravity.

Uniformly Accelerated Motion.

EXPERIMENT 32.—Arrange a trough in front of a blackboard in such an inclined position that a ball set to rolling will go say 1 foot during the first second. (The time may be marked by a pendulum which swings once a second.) The unit distance which the ball travels the first second may be marked on the blackboard.

Determine whether the ball will go three, five, and seven times as far during the second, third, and fourth seconds as during the first second.

The Path of Projectiles.

EXERCISE 33.—To the scale of $\frac{1}{16}$ inch to 16-feet, plot the path of a ball thrown upward in such a manner that it will have a vertical velocity of 256 feet per second, and at the same time a horizontal velocity of 48 feet per second. Designate your sketch as Fig. 3.

What will be the length of the whole distance traveled? How many seconds will it take to travel this distance? How long would it take the same ball to reach the ground if it were thrown merely with a vertical velocity of 256 feet per second?

Moments of Force and Machines.

EXPERIMENTS 34 AND 35.—Determine by means of the apparatus illustrated in Figs. 4 and 5 what forces must be supplied to produce equilibrium in several of the cases represented in Figs. 6–28. From these trials deduce principles which will apply to all the cases represented.

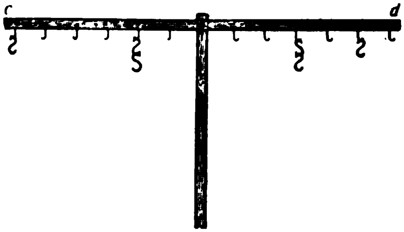

FIG. 4.—Apparatus for illustrating moments of force.

Fig. 4 represents a strip of wood, on which is pivoted a strip, *c d*, which swings freely. The weights which are hung from *c d* by means of bent pins may be made of pieces of stout copper wire, cut into equal lengths and bent into convenient shapes for hanging.

Fig. 5 represents a strip of wood, *m n*, containing several tacks, to which spring balances may be attached by means of threads. The apparatus is used horizontally upon a table.

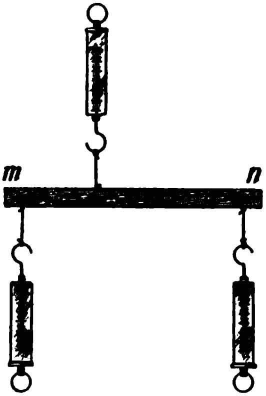

FIG. 5.—Apparatus for illustrating moments of force.

In the following exercises (36–57) certain of the forces are given in each case, and it is required to determine the remainder. It should be first calculated according to the principles, and the result afterward verified by using the apparatus represented in Figs. 4 and 5.

EXERCISE 36.

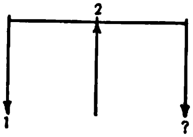

FIG. 6.

EXERCISE 37.

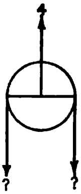

FIG. 7.

EXERCISE 38.

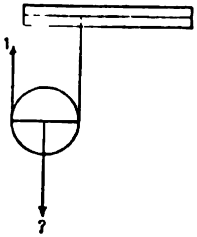

FIG. 8.

EXERCISE 39.

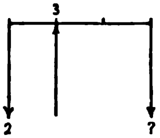

FIG. 9.

EXERCISE 40.

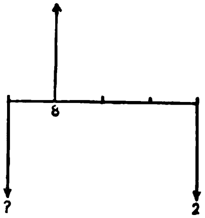

FIG. 10.

EXERCISE 41.

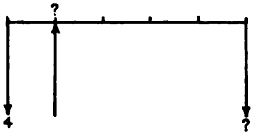

FIG. 11.

EXERCISE 42.

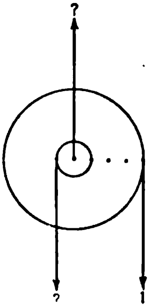

FIG. 12.

EXERCISE 43.

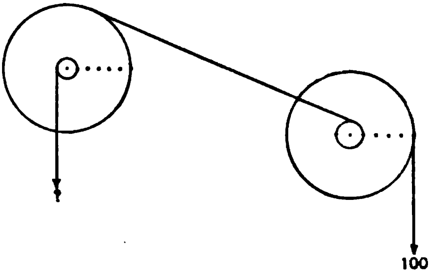

FIG. 13.

EXERCISE 44.

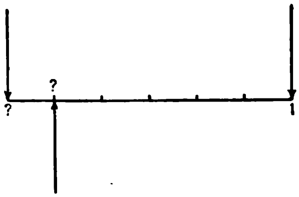

FIG. 14.

EXERCISE 45.

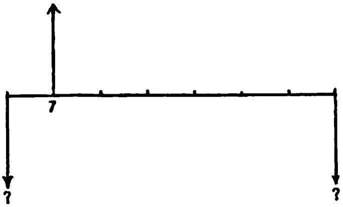

FIG. 15.

EXERCISE 46.

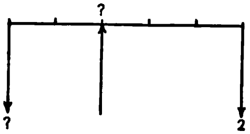

FIG. 16.

EXERCISE 47.

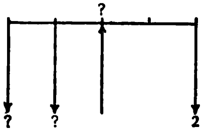

FIG. 17.

EXERCISE 48.

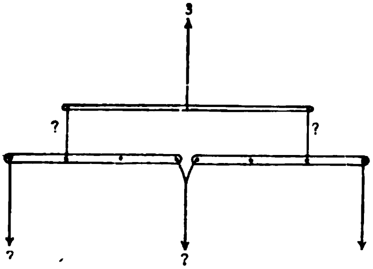

FIG. 18.—Whiffletrees for three horses abreast.

EXERCISE 49.

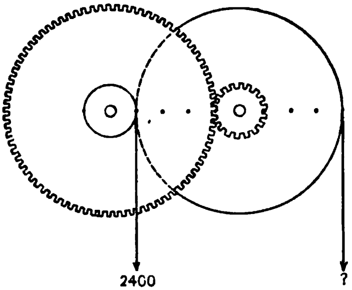

FIG. 19.—Cogwheels.

EXERCISE 50.

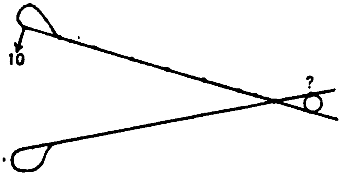

Fig. 20.—Long-handle shears for cutting metal.

EXERCISE 51.

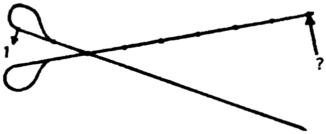

Fig. 21.—Short-handle shears for cutting paper.

EXERCISE 52.

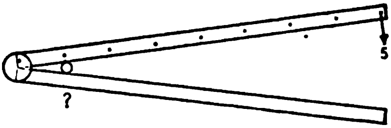

Fig. 22.—Nut-cracker.

EXERCISE 53.

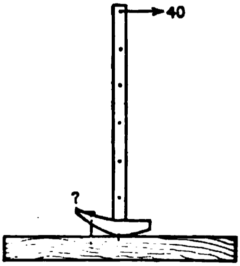

Fig. 23.—Hammer.

Exercise 54.—Fig. 24 represents a log of wood, the weight of which is 200 pounds. What force would be required at *a* or *b* or *c* to *start* to lift it?

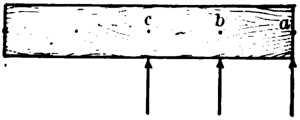

Fig. 24.

Exercise 55.—Compare forces *a* and *b* in Figs. 25 and 26 necessary to *start* the motion of the box.

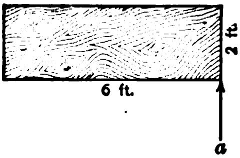

Fig. 25.

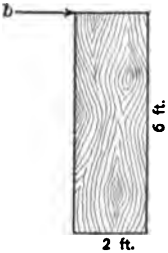

Fig. 26.

Exercise 56.—Fig. 27 represents a block of granite 2 × 4 × 8 feet. The specific gravity of granite is about 2.5. A cubic foot of water weighs 62.5 pounds. The bar, *a*, is 10 feet 4 inches long, and the fulcrum is 4 inches from the block. What force must be applied at *P* to move it?

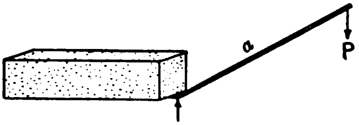

Fig. 27.

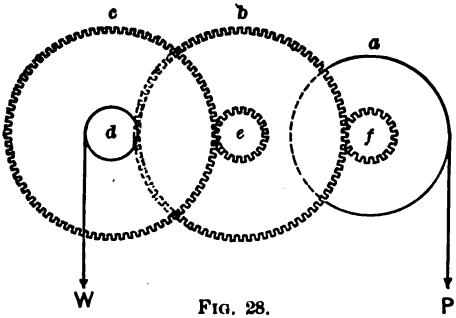

Fig. 28.

EXERCISE 57.

Diam. of $a = 6$ in. Diam. of $d = 2$ in.
" " $b = 8$ " " " $e = 2$ "
" " $c = 8$ " " " $f = 2$ "

(1) How many times as many cogs in the circumference of b as in that of f?

(2) How are the number of revolutions in a and c to be compared?

(3) What weight at W will balance 100 at P?

QUESTIONS AND PROBLEMS

1. Explain why a stream of water falling freely tends to separate into drops.

2. Why should one, in getting off and on a moving car, face the front of the car?

3. Why are steel springs used in the "spring balances"? Upon what does the efficiency of such a balance depend?

4. Why is an empty car in motion more easily stopped than a loaded one?

5. How long will it take a ball thrown upward with a vertical velocity of 192 feet per second to reach the ground?

6. Suppose a body weighing 10 pounds moves under the influence of a constant force 20 feet the first second, 60 feet the next second, and 100 feet the third second, how far will it move the fourth second? How does its momentum at the end of the fourth second compare with that at the end of the second second? Explain your method of calculation.

7. If a pendulum which swings once a second is 39 inches long, find the length of a pendulum which swings 20 times a minute.

8. How may the vibrations of a pendulum be quickened fourfold?

9. In a certain wheel and axle the diameter of the wheel is 4 feet and that of the axle is 1 foot. It is found that on account of friction a weight of 160 pounds attached to the rope which encircles the wheel is necessary to lift a weight of 600 pounds attached to the

rope which encircles the axle. How much work must a man do to lift the 600 pounds a distance of 2 feet with this machine? How much work would he need to do to lift it without the machine?

10. Why are long-handled shears used in cutting metal?

TABLE OF EQUIVALENTS

1 in. = 2.54 cm.
1 cm. = .3937 in.
1 m. = 39.37 in.
1 oz. (av.) = 28.35 gms.
1 liter = 1,000 c. c.
1 qt. (liquid) = 946 c. c.

MECHANICS OF FLUIDS

I. PRESSURE IN LIQUIDS.

Preliminary Exercises.

Exercises 1, 2, 3, and 4. Figs. 1 and 2.

First Principle.

Experiments 1, 2, and 3. Exercises 4 and 5. Figs. 3, 4, 5, and 6.

Buoyancy and Specific Gravity.

Experiments 6, 7, 8, and 9. Figs. 7, 8, and 9.

II. PRESSURE IN GASES.

Second Principle.

Experiments 10, 11, 12, 13, 14, 15, 16, 17, 18, and 19. Figs. 10, 11, 12, 13, 14, and 15. A, B, C, D, E.

Boyle's Law.

Experiment 20. Figs. 16 and 17.

III. PRESSURE TRANSMITTED.

Third Principle.

Experiments 21 and 22. Figs. 18, 19, and 20.

IV. MISCELLANEOUS APPLICATIONS.

Cartesian Diver.

Exercise 23. Fig. 21.

Siphon.

Exercise 24. Figs. 22, 23, 24, and 25.

Fountain Siphon.

Exercise 25. Fig. 26.

Lifting Pump.

Exercise 26. Fig. 27.

Force Pump.

Exercise 27. Fig. 28.

Specific Gravity of Liquids.

Exercise 28. Fig. 29.

Pressure in a Barometer Tube.

Exercise 29. Fig. 30.

Hero's Fountain.

Exercise 30. Fig. 31.

Student's Lamp.
Exercise 31. Fig. 32.
Fountain Sponge Cup or Ink Well.
Exercise 32. Fig. 33.
Constant Pressure.
Exercise 33. Fig. 34.
Pressure Gauges in Series.
Exercise 34. Fig. 35.
Questions and Problems.
Table of Specific Gravities, Weights, Equivalents, etc.

I. PRESSURE IN LIQUIDS

Preliminary Exercises.

EXERCISE 1.—To find the relative weight of water and mercury. Measure the length of the water column *a b* (Fig. 1). Measure the height of the mercury column *b c*, which balances the water column. Compute the relative weight of water and mercury.

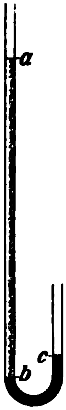

FIG. 1.

The following method is convenient for recording the results:

Length of water column *a b* = ... centimeters.

Length of mercury column *b c* = ... centimeters.

.... centimeters of mercury weigh as much as .... centimeters of water, therefore 1 centimeter of mercury weighs as much as .... centimeters of water. Mercury is .... times as heavy as water.

EXERCISE 2.—To find the relative weight of alcohol and mercury. Proceed as in the former exercise, calling the length of the alcohol column *a b*, and the length of the mercury column which balances it *b c*.

EXERCISE 3.—From the results obtained in the previous exercise calculate the relative weight of water and alcohol.

Mercury is .... times as heavy as water.
Mercury is .... times as heavy as alcohol.
Water is .... times as heavy as alcohol.
Alcohol is .... times as heavy as water.

Exercise 4.—To find the relative weights of alcohol and water. Measure the length of the alcohol column, *c b* (Fig. 2). Measure the length of the water column, *a b*, which balances it. Compute the relative weights of alcohol and water. Compare the results with those obtained in Exercise 3. Which are probably more nearly correct? Why?

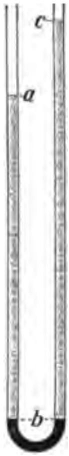

Fig. 2.

Questions.

Suppose that in Exercise 1 it were found that 1 centimeter of mercury balanced 13.6 centimeters of water. Imagine the cross section of the tube (Fig. 1) to be 1 square inch, how many cubic inches of water will it take to weigh as much as 1 cubic inch of mercury? One cubic inch of mercury weighs about ½ pound, about how much does 1 cubic inch of water weigh? One cubic centimeter of water weighs 1 gram, what is the weight of 1 cubic centimeter of mercury?

Principle I.

(*a*) *Pressure in liquids is proportional to the depth without regard to the size or shape of the vessels which contain them.* (*b*) *At any given depth it is equal in all directions.*

(*a*) Find the ratio of pressure to the depth of the water in the three given pieces of apparatus.

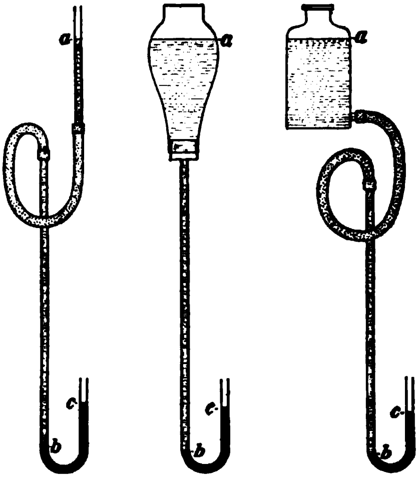

FIG. 3.

EXPERIMENT 1.—Measure the length of the mercury column *b c* (Fig. 3) in each of the three pieces of apparatus. Using for the relative weight of water and mercury the class average from Preliminary Exercise 1. (Why is this better for your use than the standard ratio?) Calculate what length of water column in each case would be necessary to balance the mercury column *b c*. Measure the length of the water column *a b* in each case. Compare these measurements with the calculated results and record the errors.

Experiment 2.—(*b*) Find the pressure downward, sidewise, and upward at a given depth—say 20 centimeters—in water in terms of centimeters of mercury.

Let the depth of the water column, *a b* (Fig. 4), in each case be 20 centimeters. Measure the length of the mercury column (*b c*), which balances this water pressure. Calculate the length of mercury column necessary to balance a water column 20 centimeters long.

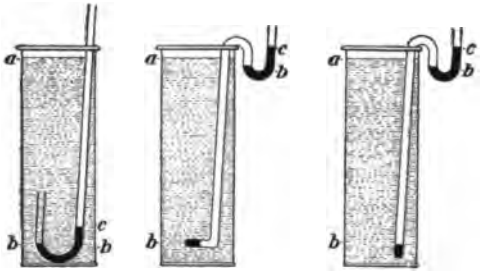

Fig. 4.

Experiment 3.—Close the lips tightly over one end of a pressure gauge, and find how long a column of mercury you can support by steady pressure of air from your lungs. How long a column of water would this pressure support? How many grams per square centimeter would this pressure support?

A cubic inch of mercury weighs about half a pound; how many pounds per square inch would this pressure support? Was this the outward pressure upon the walls of your chest and mouth during this exercise?

Exercise 4.—The vessel (Fig. 5) is filled with water. What is the pressure per square centimeter at the points *a*, *b*, *c*, *d*?

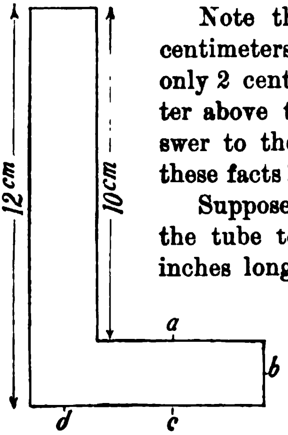

Fig. 5.

Note that *d* has a column of water 12 centimeters long standing over it, while *c* has only 2 centimeters and *b* 1 centimeter of water above them. Can you explain your answer to the above question in the light of these facts?

Suppose the area of the cross section of the tube to be 1 square inch. How many inches long would a column of water have to be to exert a pressure of ½ pound at *d*? How long a column of mercury would exert this pressure?

Exercise 5.—Three vessels (Fig. 6) have all the same depth — 10 centimeters. They are filled with water. What is the pressure per square centimeter upon the bottom of each? The bottom of each has an area of 100 square centimeters. What is the total pressure upon the bottom of each? Is the weight of water in each the same?

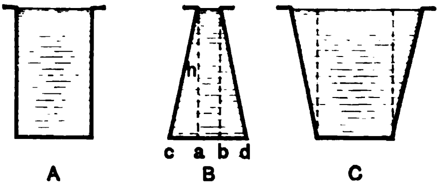

Fig. 6.

Problems.

1. A mercury pressure gauge is attached to the bottom of a tank of water. The pressure is found to be sufficient to hold up a column of mercury 15 inches. How many pounds pressure per square inch does this represent? How high is the water in the tank?

2. If the average lung pressure is 1½ pounds per square inch, how many centimeters high would it be possible to support a column of mercury in Experiment 3? How many grams pressure per square centimeter would this represent?

Buoyancy and Specific Gravity.

EXPERIMENT 6.—Find the area of the cross section of the specimen tube (Fig. 7). (Measure the diameter of the tube in centimeters, and compute the area of its cross section according to the formula πr^2.) Measure in centimeters *a b*, the depth to which the tube sinks in the water. What is the upward pressure upon each square centimeter of the bottom of the tube? What is the total pressure? This is the buoyant force. From this calculate what must be the weight of the tube with the shot which it contains, and the volume of the water which it displaces. Find the weight by using the balance. Find the volume of water it displaces by floating it in a graduate cylinder.

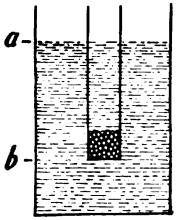

FIG. 7.

Corollaries.

A floating body displaces its own weight of the liquid. A body that sinks displaces its own volume of the liquid. The buoyant force equals the weight of the floating body. The buoyant force equals the weight of the liquid displaced. The buoyant force at any given depth is the upward pressure at that depth.

EXPERIMENT 7.—Weigh the marble (Fig. 8) in air. Weigh it when suspended in water. How much does the water buoy up? What is the volume of the marble? What is its weight compared with that of an equal volume of water? (Specific gravity.)

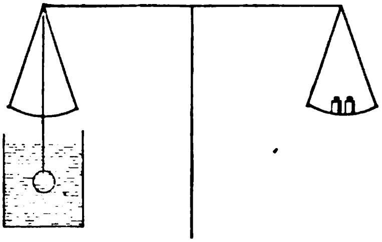

FIG. 8.

EXPERIMENT 8.—Find the volume of the marble used in the previous exercise by immersing it in a test-tube containing water, and computing, according to the formula $\pi r^2 \times h$, the volume of the cylinder of water displaced. Compare the result with that obtained in the previous exercise. Which is more reliable? Why?

EXPERIMENT 9.—Weigh a marble. Balance a tumbler of water (Fig. 9) upon a scale pan. Then suspend the marble in the water so as not to touch the bottom or sides of the tumbler, but have it completely submerged. Find how much weight must be added to the other scale pan to restore the balance. How much did the water buoy up? How much did the thread sustain? What is the volume of the marble? What is its specific gravity?

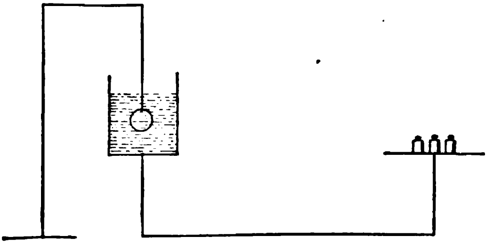

FIG. 9.

Problems.

1. Given a canal boat about like a box in shape. If the area of the bottom is 300 square feet, and it sinks 2 feet into the water, what must be its weight? What load would be required to sink it to a depth of 5 feet? One cubic foot of water weighs about 62.5 pounds.

2. A cubic inch of mercury weighs $\frac{1}{2}$ pound. Its specific gravity you have already found. (*a*) Find the pressure of the water in pounds per square inch at the bottom of a rectangular aquarium by measuring its depth. (*b*) What is the total pressure upon one of its sides?

3. How many pounds would it be necessary to lift in moving a stone under water, if the volume of the stone were 1 cubic foot and its specific gravity 2.5? If the same stone were immersed in sulphuric acid of specific gravity of 1.8, what would be its apparent weight?

4. If the specific gravity of a certain object is 2, what is its weight if it displaces 25 cubic centimeters of water?

5. If a block of wood 2 × 2 × 4 feet has a specific gravity of .5, how much will it need to be loaded in order to just submerge it in water? If you attach a load to the block you will increase its volume. What will you do with that fact? How much granite, specific gravity 2.5, would be required to sink the block?

II. PRESSURE IN GASES

Principle II.

Pressure of the air increases with, but is not proportional to, the depth. At any given depth it is equal in all directions.

EXPERIMENT 10.—Show by the balances that air has weight. Suspend from one pan of the balances an eight-ounce flask containing a rubber stopper with one hole. By means of a piece of glass tubing in the hole of the stopper, attach a small piece of rubber tubing containing a plug. Balance carefully. Remove the plug, and by means of the lungs or an air pump exhaust air from the flask. Pinch the rubber tube and replace the plug. The flask should show a decrease in weight. Add weights to restore the balance. Then detach the flask from the scale pans, invert the flask over water, and remove the plug. Measure in a graduate glass the volume of water that rises into the flask. Record the result as follows:

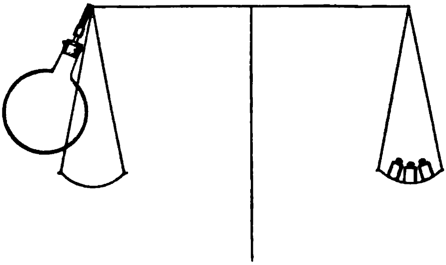

FIG. 10.

.... c. c. air weigh .... gms.

Water is 773 times as heavy as air. Compute the weight of the volume of air obtained in your experiment, and compare with the result obtained. The weight of a liter of air is about 1.29 grams.

Experiment 11.—Cause a fountain to play by atmospheric pressure, as represented in Fig. 11. By means of the lungs or an air pump exhaust air from the bottle, and then invert the bottle, allowing the rubber tube to dip into water. A fountain will play in the bottle ("fountain *in vacuo*").

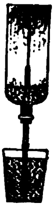

Fig. 11.

Experiment 12.—Lift the bottle (Fig. 12) by the lamp chimney after exhausting air from it. This chimney merely rests upon a rubber stopper. How does the experiment illustrate the pressure of the air?

Magdeburg hemispheres.

Experiment 13.—By means of the barometer (Fig. 13) find the pressure of the air. Read it on several successive days, and compare with the newspaper reports.

Why does a column of mercury 30 inches high represent a pressure of about 15 pounds per square inch? How many centimeters high must a column of water be to represent the same pressure? How many grams pressure per square centimeter does this indicate? Why may we not calculate the height of our atmosphere from this pressure? If the pressure of the air were proportional to the depth, how high would the atmosphere be to support a column of mercury 30 inches high?

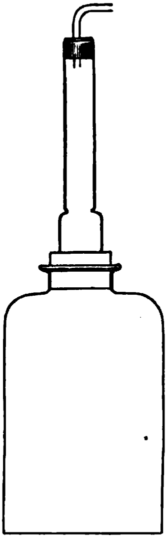

Fig. 12.

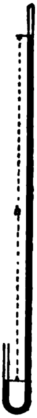

Fig. 13.

Illustrate the expansive force of the air by using the pieces of apparatus illustrated in Figs. 14 and 15, *A–E*.

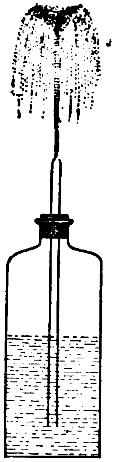

FIG. 14.

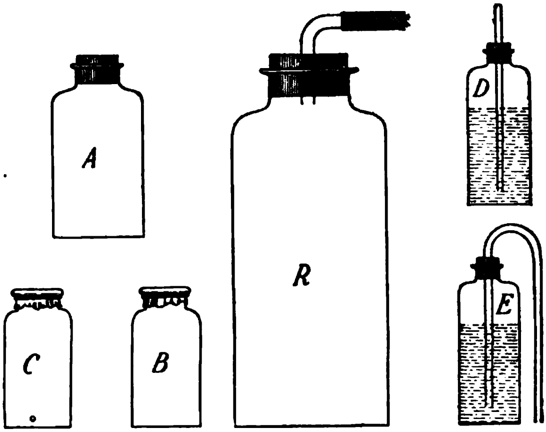

FIG. 15.

EXPERIMENT 14.—Cause a fountain to play by first condensing air in the bottle (Fig. 14) and then removing the pressure.

EXPERIMENT 15.—Close the mouth of the bottle (Fig. 15, *A*) with a rubber stopper. Put the bottle into the receiver *R*, and pump air from the receiver. Explain what occurs.

EXPERIMENT 16.—Rubber cloth is tied over the mouth of the bottle (Fig. 15, *B*). Put it into the receiver *R*. First condense air and then exhaust air, and explain what happens in each case.

EXPERIMENT 17.—Rubber cloth is tied over the mouth of the bottle (Fig. 15, *C*) and in the side of it a small hole has been bored. Try the effect on the rubber cloth of condensing and rarefying the air in the receiver *R* when the hole in the small bottle is left open, and also when it is plugged with wax. Explain. How does this illustrate the function of the Eustachian tube?

EXPERIMENT 18.—Put the small bottle (Fig. 15, *D*) into the receiver *R* and rarefy the air. Explain why the fountain plays. How might the apparatus be arranged so that the fountain would play into the small bottle instead of into the receiver?

EXPERIMENT 19.—Put the bottle (Fig. 15, *E*) into the receiver *R*. How may the water be made to flow from the small bottle into the receiver? How would it be possible to make the water flow from the receiver into the small bottle?

Boyle's Law.

EXPERIMENT 20.—By means of the Boyle's law apparatus, find the relation of volume to pressure in air.

Fig. 16 shows increase in pressure, and consequent decrease of volume of air in the closed end, *a b*, of the tube. Fig. 17 shows decrease of pressure and increase of volume. Start with the apparatus horizontal. Under how great pressure then is the air in the closed end? By what means may we increase the pressure upon it? Try increasing the pressure to twice what it originally was. How

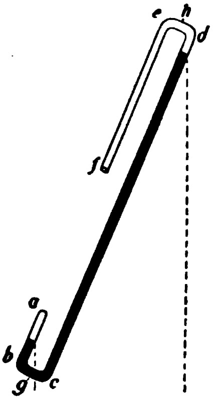

FIG. 16.

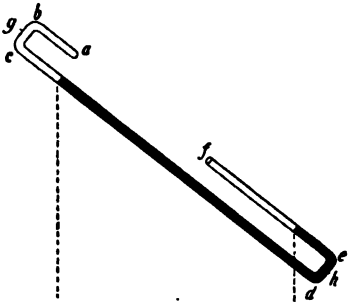

FIG. 17.

long a mercury column is pressing on the inclosed air? What has its volume become? How long a mercury column will represent $\frac{1}{3}$ of the original pressure upon it? Try increasing the pressure by this amount, and find what the volume of the air has become.

By tilting the tube in the opposite direction, increase the volume of the air to twice what it originally was. By what length of mercury column has the pressure been decreased? How does the pressure now compare with the original pressure? Try reducing the volume to $\frac{3}{4}$. What is the pressure upon it? Try increasing the volume to $\frac{3}{2}$. What is the pressure upon it? What is Boyle's law?

Problems.

Disregard changes due to temperature. If a cubic foot of air weighs 1.28 ounces at the sea level, what would it weigh at a height of 3 miles? If a balloon displaces 3,000 cubic feet of air, how many pounds of buoyant force would it have at the sea level? How many at a height of 3 miles? In what way would changes due to temperature affect these results?

How deep in water must a bubble of air be liberated in order that when it reaches the surface it may have twice as great a volume as when set free?

An object having a volume of 1 cubic foot weighs 2 ounces. What would it weigh in a vacuum?

III. PRESSURE TRANSMITTED

Principle III.

Pressure exerted upon a fluid (liquid or gas) inclosed in a vessel, is transmitted equally in all directions—the total pressure upon the walls of the vessel being proportional to the area.

See how the principle is illustrated in the exercises which follow.

Experiment 21.—Using a single pressure gauge containing mercury, find how much pressure in grams per square centimeter you can exert with your lungs; connect 2 pressure gauges " in parallel " and note the pressure as indicated by each; connect 3 pressure gauges " in parallel " and note the pressure as indicated by each. (See Fig. 18.)

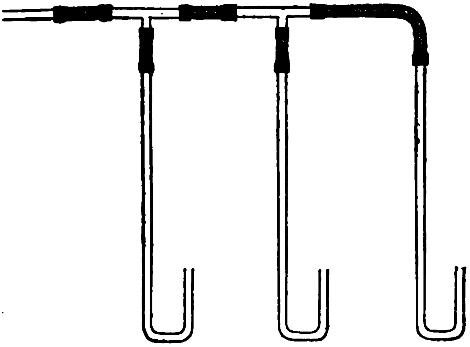

Fig. 18.

Experiment 22.—Using the apparatus represented in Fig. 19, find how many pounds (or grams) may be raised by the pressure which you may exert from your lungs.

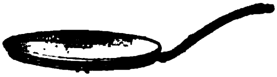

Fig. 19.

Calculate the area of the rubber cloth according to the formula (πr^2). Consider the pressure exerted by the lungs $1\frac{1}{2}$ pounds per square inch. What total pressure on the rubber cloth does this represent?

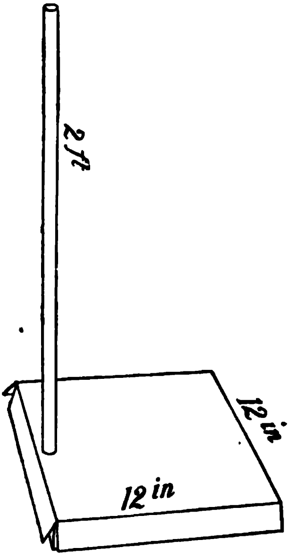

Fig. 20.

Problem.

Referring to Fig. 20, suppose the tube to be filled with water, what is the total force in pounds which tends to burst the cover of the box?

IV. MISCELLANEOUS APPLICATIONS OF PRINCIPLES

Examine, operate, and explain the pieces of apparatus illustrated in the following figures.

The Cartesian Diver.

EXERCISE 23.—The bottle *a* (Fig. 21) contains 1 cubic centimeter of air. If we exert a pressure of 5 pounds per square inch upon the rubber top, what will the volume of air in *a* become? Will it sink? Why?

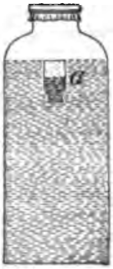

FIG. 21.

The Siphon.

EXERCISE 24.—Explain the working of the apparatus illustrated in each of the figures 22–25. What is it necessary to do to start the action in each case? With what force are the siphons in Figs. 22, 23, and 24 operating? Why?

"Tantalus cup."

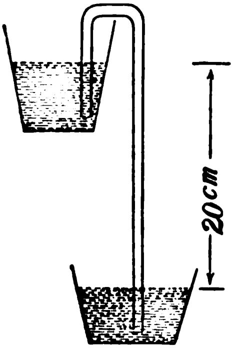

FIG. 22.

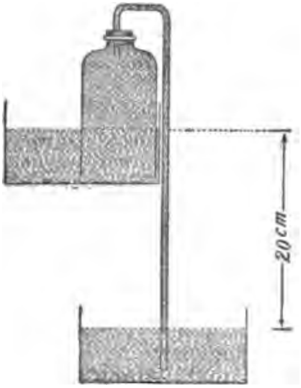

FIG. 23.

Fountain Siphon.

EXERCISE 25.—Under how great pressure is the fountain (Fig. 26) operating?

Why is the rubber cloth drawn downward into the chimney?

To what must the tension of the air in the chimney be reduced in order that the water may be raised from *c* to *a*?

Sprengel's pump.

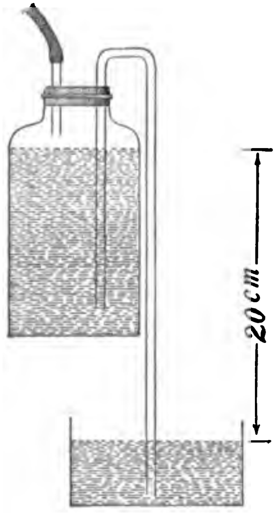

FIG. 24.

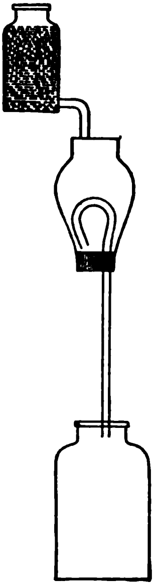

FIG. 25.

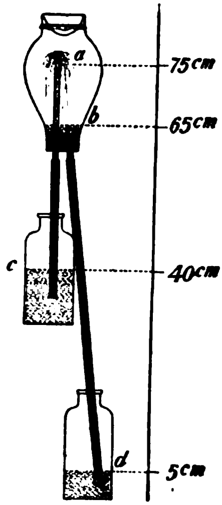

FIG. 26.

Lifting Pump.

EXERCISE 26.—To what tension must the air in the cylinder of the pump (Fig. 27) be reduced in order that the water shall rise to enter it? How much must its volume be increased to produce that tension. Ignore the volume of air in the tube.

About how high may water be raised by a perfect pump of this variety? Why?

Force Pump.

EXERCISE 27.—Fig. 28. Why is the flow of water from the jet continuous, while in the case of Fig. 27 it was intermittent?

Specific Gravity of Liquids.

EXERCISE 28.—Fig. 29. By putting the tube *e* to the mouth, slightly reduce the tension of the air in the two tubes. Pinch the rubber tube, and read and record the length, *a b*, of the water column, and the length, *c d*, of the alcohol column. Compute from this the specific gravity of alcohol. Suppose the water column were 10 centimeters high. How high would a corresponding sulphuric acid column stand? What ether column would an alcohol column 12 centimeters high balance?

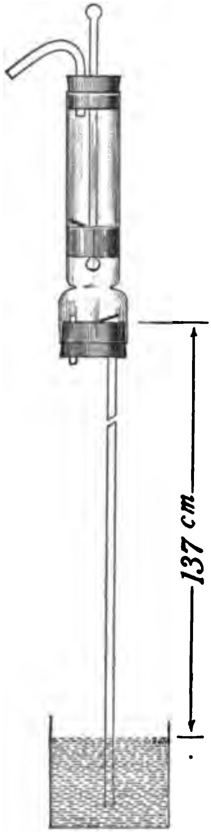

FIG. 27.

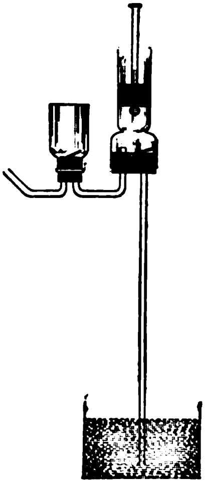

FIG. 28.

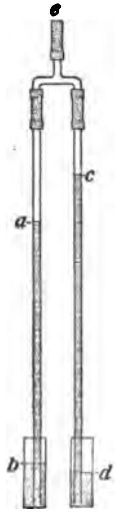

FIG. 29.

For table of specific gravity see page 42.

Pressure in a Barometer Tube.

EXERCISE 29.—Including atmospheric and water pressure, what is the pressure in grams per square centimeter at the points *a*, *b*, *c*, *d*, and *e*, Fig. 30?

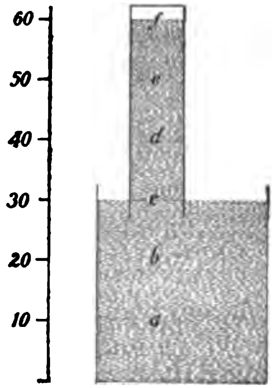

FIG. 30.

A column of water 1,033 centimeters high represents the pressure of one atmosphere. What is the tension in grams per square centimeter of the air in the upper part of the cylinder above *f*?

When the barometer stands at 30 inches, what is the pressure inside the tube at points 10, 20, and 30 inches above the zero point?

Hero's Fountain.

EXERCISE 30.—Suppose the surface of the water in *D* and *M* (Fig. 31) to be 75 centimeters higher than that in *N*, and suppose *a* to be 15 centimeters above the surface of the water in *M*. If you place your finger on *a*, how much pressure in grams per square centimeter is exerted upon the surface of the water in *M*, and what pressure is required to stop the flow at *a*?

Would the fountain flow at the same height whether the bottle *M* were raised or lowered?

What would be the effect of raising or lowering the bottle *D*?

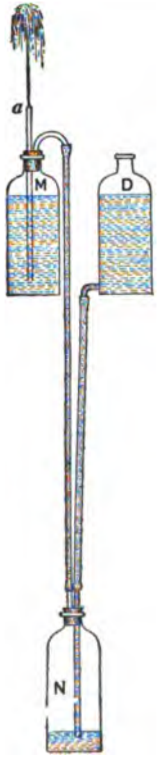

FIG. 31.

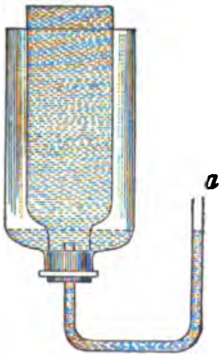

FIG. 32.

Student's Lamp.

EXERCISE 31.—Fig. 32. Why does the water not flow out of the tube at *a* (Fig. 32)?

Fountain Sponge Cup or Ink Well.

EXERCISE 32.—What are the advantages of a fountain sponge cup or ink well? Why does not the water in the small cup rise above *a* (Fig. 33)?

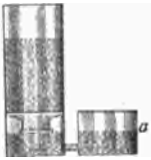

FIG. 33.

Constant Pressure.

EXERCISE 33.—What is the purpose of the inverted bottle of water (Fig. 34)? What does the lower bottle illustrate about pressure in liquids?

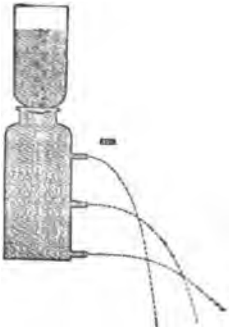

FIG. 34.

Pressure Gauges in Series.

EXERCISE 34.—Refer to Experiment 21. Connect the three pressure gauges *in series* (Fig. 35), and predict how high mercury in each will be forced up by the pressure which you may exert with your lungs. Try it, and compare the result with your prediction. Compare this result with that obtained in Experiment 21, when they were connected *in parallel*.

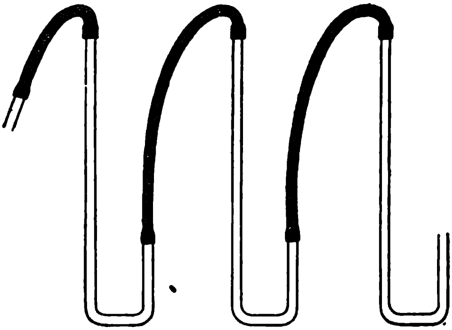

FIG. 35.

Questions and Problems

1. A cubic foot of ice weighing 56¼ pounds is floating in water, and $\frac{1}{10}$ of its volume rises above the surface of the water. Show how you may compute from this the weight of a cubic foot of water.

2. Granite is about 2½ times as heavy as water; how much would you be obliged to lift while holding a cubic foot of it submerged in water?

3. A mercury pressure gauge attached to a water faucet registers 30 inches. Compute the height of the water in the tank above the mercury in the pressure gauge, and the pressure it exerts in pounds per square inch and grams per square centimeter.

4. How much will a vessel weighing 50,000 pounds have to be loaded in order that it shall displace 1,000 cubic feet of water?

5. A certain spar is 20 feet long. Its cross sections are circles, and its average diameter is 1 foot. The specific gravity of the wood is .5. What is the buoyant force of the water upon the spar? How much iron (specific gravity 7.75) will be required to sink it?

6. How great will the diameter of an apparatus like that in Fig. 18 need to be in order that, with a pressure of 1⅛ pounds, it will be possible to lift a weight of 100 pounds?

7. What would be the buoyant force, at a height in the atmosphere where the barometer would register about 7⅛ inches, upon an object having a volume of 5 cubic feet?

8. In a large wide-mouthed bottle of water (Fig. 21) a small vial is inverted, having just enough air in the upper part to float it. The weight of the vial is 3.5 grams, the air which it contains is 2.5 cubic centimeters. What must be the volume of glass in it, and what is its specific gravity? The rubber cloth is air-tight over the mouth of the large bottle. If now we exert a pressure of 5 pounds per square inch upon the rubber, what will the volume of the air in the vial become? Will it sink? If so, with how much force will it press upon the bottom of the large bottle? If now we remove the pressure from the rubber cloth, and pull upward upon it with a force of 5 pounds per square inch, what will the volume of the air in the vial become? Will the vial rise above the surface of the water in the large bottle? If so, what volume will emerge?

9. If an object whose volume is 1 cubic foot weighs in air 25 grams, what would it weigh in a vacuum?

TABLE OF SPECIFIC GRAVITIES, WEIGHTS, EQUIVALENTS, ETC., USED IN THE FOREGOING CHAPTER

These values are approximate.

Specific gravity of mercury	13.60
“ “ alcohol	.80
“ “ sulphuric acid	1.80
“ “ ether	.74

Weight of 1 cubic inch of mercury	.50 lb.
“ 1 “ centimeter of mercury	13.60 gms.
“ 1 “ “ water	1.00 gm.
“ 1 “ foot of water	62.50 lbs.
“ 1 liter of water	1,000.00 gms.
“ 1 “ air	1.29 “
“ 1 cubic foot of air	1.28 oz.

1 centimeter = .3937 in.
1 inch = 2.54 cm.
1 decimeter = 10 cm.
1 meter = 10 dm.
1 meter = 100 cm.
1 meter = 39.37 in.

Area of circle = πr^2 ($\pi = 3.1416$).
Volume of cylinder = area of cross section × length.
Volume of sphere = $\frac{1}{6}\pi D^3$.

HEAT

- I. How Heat is produced.
  - A. *Heat produced by Friction.*
    - Experiments 1, 2, 3, and 4.
  - B. *Heat produced by Pressure.*
    - Experiments 5, 6, and 7. Figs. 1, 2, and 3.
  - C. *Heat produced by Chemical Action.*
    - Experiment 8.
- II. Some Effects of Heat.
  - *Expansion of Gases.*
    - Experiments 9, 10, and 11. Figs. 4 and 5.
  - *Change of State.*
    - Experiments 12 and 13. Fig. 7.
  - *Expansion of Liquids—Mercury Thermometers.*
    - Experiments 14, 15, 16, and 17. Figs. 8 and 9.
  - *Expansion of Solids.*
    - Experiments 18, and 19. Fig. 10.
  - *Evaporation—Distillation—Dew-point.*
    - Experiments 20, 21, 22, 23, 24, 25, 26, 27, and 28. Figs. 11 and 12.
- III. How Heat is transferred.
  - A. *Heat transferred by Conduction.*
    - Experiments 29, 30, 31, 32, 33, 34, and 35. Fig. 13.
  - B. *Heat transferred by Convection.*
    - Experiments 36, 37, and 38. Figs. 14, 15, 16, 17, and 18.
  - C. *Heat transferred by Radiation.*
    - Experiments 39, 40, 41, and 42. Figs. 19, 20, and 21.
- IV. Specific Heat and Calorimetry.
  - Experiment 43.
- V. Latent Heat.
  - A. *Heat disappears when Solids liquefy.*
    - Experiments 44 and 45.
  - B. *Heat disappears when Liquids vaporize.*
    - Experiment 46.
  - C. *Heat reappears when Vapors liquefy.*
    - Experiment 47. Fig. 22.
  - D. *Heat reappears when Liquids solidify.*
    - Experiment 48.
  - Questions and Tables.

I. HOW HEAT IS PRODUCED

A. **Heat produced by Friction.**

EXPERIMENT 1.—Fasten a strip of tin to a block of wood and grind the tin upon stone or wood until it is hot enough to light a small piece of phosphorus upon a plate.

Hot axle on cars; on wagons. Machinery warms up while running. What is done to obviate this? Saw gets hot while sawing wood. Grease used to reduce friction, and thereby diminish heat. The charring of a stick of wood by rubbing it against a rapidly moving wheel.

EXPERIMENT 2.—Produce sparks by striking a pebble a glancing blow against a rasp.

Sparks produced by emery wheel. Horse's shoe striking the pavement. Scissors grinder. Car brakes.

EXPERIMENT 3.—Try to light a *friction* match by drawing it across first a very smooth surface (a pane of window glass), and second a rather rough surface (a pane of ground glass). Why does it light more easily upon one surface than the other?

EXPERIMENT 4.—Bend a strip of tin back and forth rapidly until it gets hot. Why?

Rocks fused by flexing of the earth's crust. Is animal heat due in any degree to friction?

B. Heat produced by Pressure.

Experiment 5.—With a pump condense air in a bottle containing a thermometer to indicate changes of temperature (Fig. 1). Exhaust air from the bottle, and notice whether the thermometer falls.

Experiment 6.—With a pair of forceps pinch the rubber delivery tube (Fig. 2) to check the flow of steam. Note the effect upon the temperature. Do not force the temperature above 105° C.

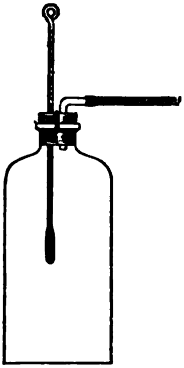

Fig. 1.

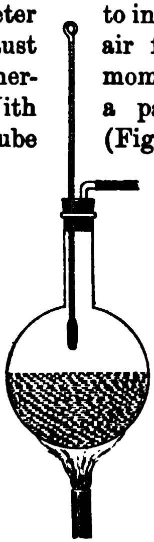

Fig. 2.

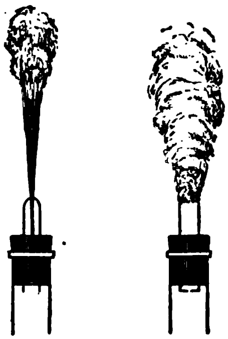

Fig. 3.

Experiment 7.—Notice difference in temperature in the steam which comes from two flasks (Fig. 3). The delivery tube of one is nearly closed and the steam rushes out under considerable pressure, while from the other it flows slowly. Try the temperature, both with the hand and with the thermometer.

Steam jet from locomotive. Fall of temperature when a "soda-water" bottle is uncorked. Manufacture of ice. Internal heat of the earth. Heat of the sun.

C. Heat produced by Chemical Action.

Experiment 8.—Hold in the palm of one hand a small dish containing a piece of quicklime as large as a hen's egg. Add cold water, and note the heat which will be produced. Give plenty of time, and note how the heat increases. Use the thermometer, and see if the temperature rises as high as the boiling point of water (100° C).

Compost heaps get very warm, by reason of the chemical decomposition that is going on in them. Piles of green grass, new grain, new hay, new flour, cotton with seed in it, or oily cotton waste all produce heat for the same reason. Animal heat.

II. SOME EFFECTS OF HEAT

Expansion of Gases.

Heat acts like a force within a mass to drive its particles farther apart. It expands gases, liquids, and solids.

Experiment 9.—Heat a flask filled with air, having a rubber cloth tied air-tight over its neck (Fig. 4). Notice that when the flask is heated the rubber cloth bulges up. Allow the flask to cool until you can bear your hand on it, then pour cold water over it. Why is the rubber cloth now pushed downward into the neck of the flask?

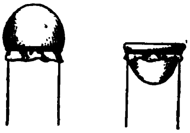

Fig. 4.

Experiment 10.—Prepare some hot soapsuds. Now roll a tumbler in the suds. Take it out and shake once or twice, so as to entrap in the tumbler some cold air. Then bring the tumbler, mouth downward, on a plate containing enough soapy water to seal the mouth of the tumbler. Why do bubbles first appear on the outside of the tumbler? Explain their final appearance on the inside.

This phenomenon frequently occurs in the kitchen when tumblers are taken from the suds.

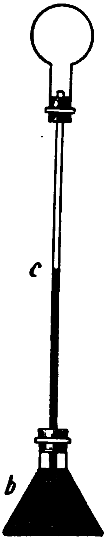

Fig. 5.

Experiment 11.—Hold the bulb of the air thermometer (Fig. 5) in the palm of your hand for a short time, and note the height of the liquid in the tube. Rub the palms of your hands together vigorously, and again close one of them around the thermometer bulb. Note the height of the liquid in the tube. The tube *c* goes through an ordinary cork and dips into some colored liquid in the bottle *b*. Why does the liquid rise in *c* when the temperature falls, and fall in the tube when the temperature is raised?

Why is an air thermometer so sensitive?

Hot-air engines.

Change of State.

Heat changes solids to liquids and liquids to gases by expansion.

EXPERIMENT 12.—Melt some paraffin in a small cup or jar over boiling water until the cup is even full of the liquid paraffin. Allow it to cool, and notice that it contracts very perceptibly on cooling. Illustrate by a sketch, and designate it Fig. 6.

Why can not paraffin and wax candles be cast in a mold?

EXPERIMENT 13.—Fill a test-tube about one third full of water. Plug the tube by inserting halfway into it a rubber stopper that can be with difficulty forced into it. Heat the water in the test-tube until the rubber stopper is forced out (Fig. 7).

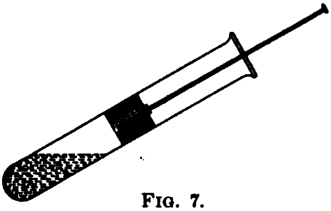
FIG. 7.

Steam engines.

Expansion of Liquids—Mercury Thermometers.

EXPERIMENT 14.—Repeat Experiment 11 with a mercury thermometer. Find what is the temperature of your blood upon either Fahrenheit or centigrade scale, and translate it into the corresponding temperature upon the other scale. Do the same with the temperature of the air in the room, the water from the faucet, or other specimens of water which may be furnished you.

On the centigrade scale the freezing point is 0° and the boiling point 100°. On the Fahrenheit scale the freezing point is 32° and the boiling point 212°. Therefore there are 100° between the freezing and boiling points on the centigrade scale, and 180° between the freezing and boiling points on the Fahrenheit. Nine Fahrenheit degrees are equal to five centigrade degrees; or, in other words, a centigrade degree is $\frac{9}{5}$ of a Fahrenheit degree, and a Fahrenheit degree is $\frac{5}{9}$ of a centigrade degree.

Experiment 15.—Note the size of bore of the tube of a broken thermometer. What is the advantage of having the tube so small and the bulb so large? What advantage in thin walls for the bulb?

Experiment 16.—Determine the 0 point on your centigrade thermometer (or 32° on a Fahrenheit thermometer); also determine the 100° point (or 212° point). Use apparatus represented in Figs. 8 and 9 for this purpose.

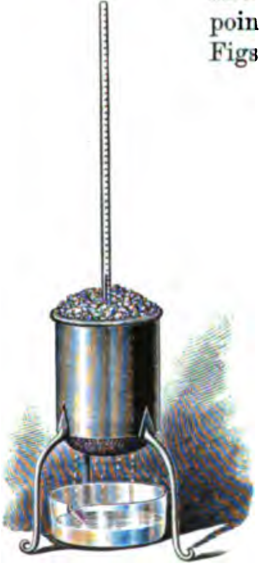

FIG. 8.

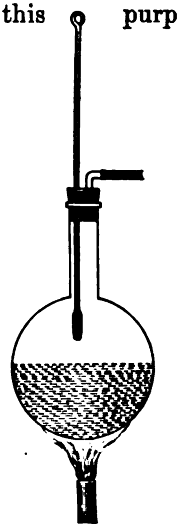

FIG. 9.

Contraction by cold is in the following case more than balanced by expansion of crystallization.

Experiment 17.—Fill a one-ounce narrow-mouthed bottle with water, cork it, and surround it with a mixture of ice and salt in a tumbler. In fifteen or twenty minutes the water should have frozen and broken the small bottle.

Why does ice float upon water?

The above experiment illustrates the expansion of crystallization of various substances—for example, type metal. What kind of substances may be cast in molds?

Expansion of Solids.

EXPERIMENT 18.—Illustrate the expansion of solids by heating a fine wire stretched between two supports.

EXPERIMENT 19.—Heat two strips of metal, *a* and *b* (Fig. 10), as uniformly as possible by holding them in a flame. (*a* is a strip of brass, and *b* a strip of iron.) Notice that the metals expand unequally. Which expands the more?

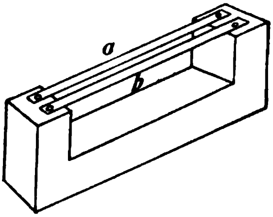

FIG. 10.

Examine a metal thermometer, and explain the principle upon which it is constructed.

Evaporation—Distillation—Dew-point.

EXPERIMENT 20.—Warm a plate and put it by the side of a cold plate. Put a drop of water upon each, and note the time of evaporation in both cases.

Dishes taken from hot rinsing water dry more quickly than when taken from cold water. Clothes dry more rapidly when wrung out of hot water than cold water; when hung near a hot stove than in a cold room. The body dries faster when coming from a hot bath than from a cold one.

Heat acts like a force within a mass to drive its particles farther apart, and thus expands liquids into vapors. Vapors condense to liquids again on cooling. By this process of distillation we are able to recover salts from solutions.

Experiment 21.—Make a solution of salt in water (about half a teaspoonful in an ounce of water) and distill a portion of it (Fig. 11). Taste the solution and the distillate. Did the distillate pass through an invisible state in the process of distillation? Pour the solution into an evaporating dish, and evaporate to dryness over a water bath. How does the amount of salt left compare with that taken for the experiment?

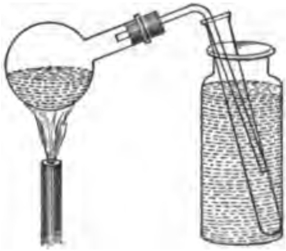

Fig. 11.

The process of distillation is illustrated by what goes on in the laundry. The water evaporates from the boiler, and is condensed to drops upon the window pane. This process goes on in a large way in Nature—fog, mist, clouds, rain, and dew.

Experiment 22.—In a bright metal cup put water, and add slowly small pieces of ice. Stir with a thermometer, and notice the temperature of the water at the moment dew begins to appear upon the outside of the cup. Slowly add water, stir continually, and notice the temperature of the water at the moment the dew disappears. If the two readings agree closely (within 2°), average them. This average temperature is the "dew-point."

Drops of water upon an ice pitcher. "Seeing the breath" in a cold atmosphere. Frost on the window pane. The evaporation from ocean and lakes which have no outlets must be equal to all the water which is supplied to them by rivers and rain.

Experiment 23.—Arrange the following according to the facility with which they evaporate at the temperature of the room: Ether, alcohol, water, gasoline, benzine.

Experiment 24.—Cause mercury to evaporate by heating it in a test-tube. Notice the drops of mercury that condense on the cooler portions of the tube.

Some substances appear to pass directly from the solid to the gaseous state without passing through the liquid state.

Experiment 25.—Heat a test-tube or flask for a few moments, and after taking it from the flame drop into it a crystal of iodine. Examine also a bottle in which iodine has stood, and notice evidences of evaporation at the ordinary temperature.

The evaporation of camphor. The evaporation of ice on cold, *windy* days. Clothes "freezing dry."

Relation of Pressure to Evaporation.

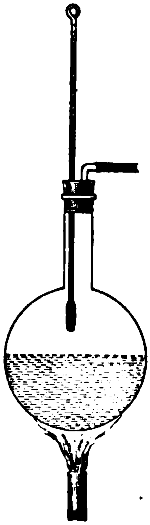

Fig. 12.

Experiment 26. — Breathe into two 8-ounce flasks so as to cloud them with moisture. Pump air from one of the flasks, and compare the evidences of evaporation in the two flasks.

Experiment 27.—Use apparatus represented in Fig. 12. Heat the water nearly to the boiling point, remove the lamp, and connect the exhaust nipple of the pump. Take a few strokes, and note the effect upon the rate of evaporation; also note the temperature as indicated by the thermometer. Exhaust still further, and see if you can make water boil at a temperature, say, of 75° C.

Refer to Experiment 6. Temperature of water in engine boilers. Extraction of gelatin from bones. Papin's Digester.

Boiling point on mountain tops. Vacuum pans in sugar refineries, milk condensers, etc.

Effect of Currents of Air upon Evaporation.

Experiment 28.—Evaporate drops of water from two plates. Blow across one of them.

Clothes dry more quickly on windy than on still days. "Muggy days." Humidity.

III. HOW HEAT IS TRANSFERRED

A. Heat transferred by Conduction—Conductors Good and Bad.

Experiment 29.—Heat at their conjunction an iron and a copper wire which have been linked together. Pass the hand along each wire toward the flame to determine which is the better conductor of heat. Burn a match at one end; why is there no heat perceptible at the other end? Melt a short piece of glass at one end while holding the other end in the hand.

Experiment 30.—Heat two iron wires in the flame—one a very thin wire taken from the wire gauze to be used in the next exercise, and the other a thick one. Why does the small wire quickly reach the melting point of iron, while the larger one is scarcely heated red hot?

Experiment 31.—Hold in a flame a piece of thin wire gauze made of the same wire as above, with meshes about forty to the inch. Why is it not easily heated red hot? Why does not the flame pass up through the gauze? By means of a lighted match determine whether unburned gas is passing up through the gauze.

Experiment 32.—Extinguish the flame of the Bunsen burner, lay the wire gauze over the mouth of the lamp, turn on the gas, and light it above the gauze and slowly raise the latter. Why does not the flame extend through the gauze to the mouth of the lamp?

Experiment 33.—Use apparatus to illustrate the Miners' Safety Lamp as represented in Fig. 13. Light the lamp and pass it into a bottle of illuminating gas. Try bringing an unprotected flame to the bottle filled with illuminating gas. Explain these phenomena in the light of Experiments 31 and 32.

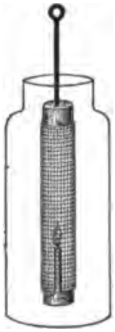

Fig. 13.

Experiment 34.—Float an evaporating dish upon a vessel containing a small amount of water (a beaker is convenient). Immerse a small thermometer inverted in the water, with the bulb very near to but not touching the evaporating dish. Pour alcohol into the evaporating dish and light it. Notice that the water boils where it comes in contact with the sides of the dish. How is the thermometer affected? Try the same experiment with the thermometer bulb downward. In each case, after taking the thermometer reading, stir the water and read again. Is water a good or poor conductor of heat? Does the summer's sun heat bodies of water to any great depth?

Experiment 35.—Put a small thermometer into a test-tube, and heat the upper end of the tube in the flame. Does the air in the tube conduct heat to the thermometer? Remove the flame and tip the tube so that its mouth shall be slightly below the other end. Note the change in the thermometer.

Conducting and non-conducting materials used for clothing; used for handles of stove utensils; wrappings for hot stones, for furnaces, for steam pipes. How are the crops protected by snow in winter? Double windows used in houses in winter time.

B. Heat transferred by Convection.

EXPERIMENT 36.—Cause a current of air to pass through a pasteboard box by means of two Argand lamp chimneys and a lighted candle, as in Fig. 14. To detect the course of the current, bring a smoking lamplighter to the top of the chimney in which the candle is burning. Then bring it over the other chimney, and explain why smoke goes down that chimney and up the other. Also cause a current of air to pass through a common lamp chimney by using a cardboard partition and a lighted candle, as in Fig. 15.

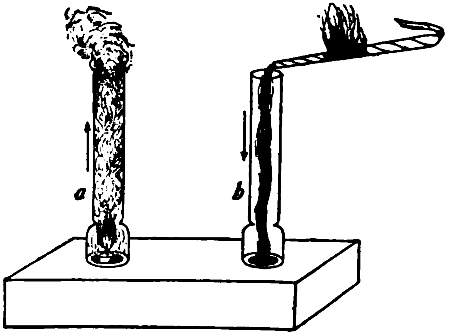

FIG. 14.

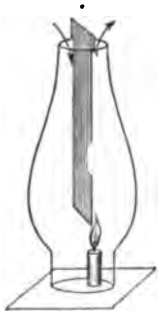

FIG. 15.

EXPERIMENT 37.—Place a small flame under one side of a beaker with a metal partition in it (Fig. 16). Drop in flakes of something to show convection currents in water.

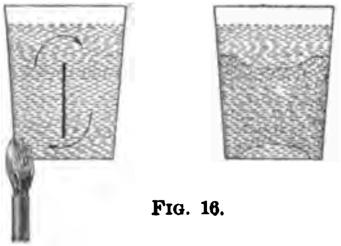

FIG. 16.

Experiment 38.—Illustrate how currents of water move into the hot-water tank by using apparatus like that in Figs. 17 and 18, where *A* represents the boiler, *B* the pipes, and the burner the kitchen range.

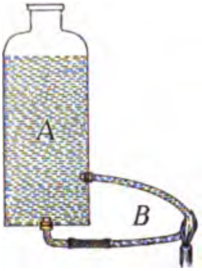

Fig. 17.

Hot-water pipes in the house. Winds. Land and sea breezes. Ocean currents. Ventilation.

C. Heat transferred by Radiation.

Experiment 39.—Cause the radiometer to move by the radiation from your hands; by the radiation from a cup of hot water.

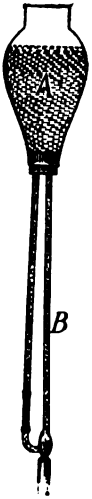

Fig. 18.

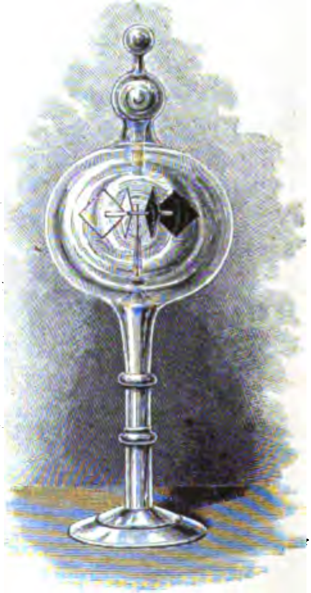

Fig. 19.

Experiment 40.—Smoke the bulb of one air thermometer, and cover the bulb of another with tin foil. Hold a basin of hot water over them (Fig. 20). Which absorbs the most heat? Remove the tin basin and watch the movement of the liquid in each. Which radiates the most heat?

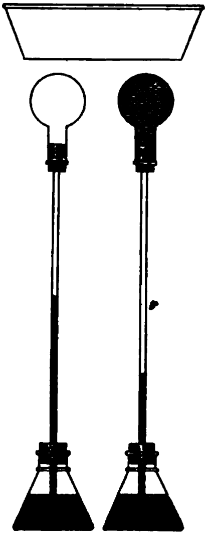

Fig. 20.

Experiment 41.—In Fig. 21 *a* represents a disk of wood well painted. A hole is bored through the center of this disk so that it will fit tightly upon the tube of a Bunsen burner. One sector of this disk (*b*) is covered with tin foil, another sector (*c*) is covered with thin sheet asbestos, a third sector (*d*) is left unprotected. Light the burner and support over the flame a basin of water. After subjecting it to this radiation for half an hour or so, remove the coverings from the disk, and note which sector appears to have been heated most.

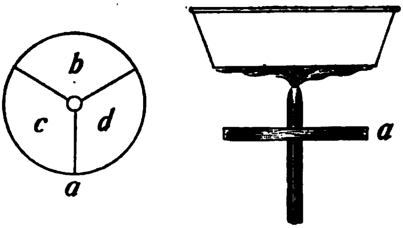

Fig. 21.

Experiment 42.—Remove the flasks from the air thermometers (Fig. 20). Fill them with hot water and note their relative rate of cooling.

How do we get heat from an open fireplace? Would we be able to receive heat from the fire if there were no atmosphere or matter of any kind in which conduction or convection could occur? How do we get heat from the sun? The hotbed. The greenhouse. Why do dew and frost collect more upon some things than upon others? How does snow protect crops?

IV. SPECIFIC HEAT AND CALORIMETRY

EXPERIMENT 43.—Have 200 cubic centimeters of water at the temperature of the room in each of two vessels (calorimeters). (Bright metal cups will serve the purpose.) Note the temperature. In a third vessel have 200 cubic centimeters of water, with a piece of lead in it weighing 200 grams. Have a thread attached to the lead, so that you may transfer it from one vessel to another. Cover this third vessel to prevent loss of water by evaporation, and heat it nearly to the boiling point of water. Remove the lamp, take the temperature of the water (and lead?), and quickly transfer the lead to one of the aforementioned vessels of water and into the other pour the hot water. Stir the hot and cold water together, and move the lead about for a few moments to make the temperature in each uniform. Now note the resulting temperature in each. Calculate from the above results the specific heat of lead. What are some of the sources of error in the experiment? Try the experiment over again, eliminating as many of the sources of error as possible. What is the difference between temperature and quantity of heat?

V. LATENT HEAT

A. Heat disappears when Solids liquefy.

Experiment 44.—Take the temperature of some water. Wipe the thermometer dry and take the temperature of some fine salt. Mix salt in the water, and take the resulting temperature.

Experiment 45.—Take the temperature of some shaved ice. Mix salt with the ice, and take resulting temperature. Does the ice liquefy faster when mixed with salt than otherwise? While it is changing from solid to liquid, how is its temperature changing? Why is salt put upon icy pavements?

Freezing mixtures.

B. Heat disappears when Liquids vaporize.

Experiment 46.—Take the temperature of ether in the bottle. Put a little in a watch crystal or an evaporating dish, and note its temperature while it is evaporating. Blow across it. Why? Note the temperature. Put a drop of water upon a block of wood, and set the watch crystal containing ether in the water on the block. Blow across the ether until the drop of water freezes.

Ice machines. The water bath. The double boiler. Animal heat reduced by perspiration. Sprinkling with water for the purpose of cooling. "Muggy days." Humidity. Why is it difficult to cook on a mountain top? Freezing produced by reducing the pressure.

C. Heat reappears when Vapors liquefy.

EXPERIMENT 47.—Take 200 grams of water in a flask (Fig. 22, *a*). Note its temperature. Pass steam into it from another flask (*b*) until its temperature rises, say, 50°. Weigh to find how much water has been added by condensation of steam. How many units of heat have been added to the flask? How many are due to the liquefying of the steam? How many units of heat for each unit of steam liquefied? (The stopper in *a* must have holes to permit of ready expansion.)

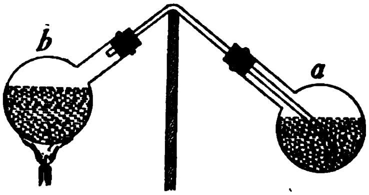

FIG. 22.

Steam heating of buildings. Temperature in the center of a rain storm.

D. Heat reappears when Liquids solidify.

EXPERIMENT 48.—Put 27 grams of sodium sulphate into 50 grams of water in a flask, heat to 34°, and stir until all is dissolved. Allow it to stand very quietly, so as to cool without depositing crystals. When it has cooled to the temperature of the room, put a thermometer into the liquid and stir. Note the rise in temperature as the sodium sulphate deposits.

Temperature in the center of a snowstorm. Tubs of water put in a cellar to keep vegetables from freezing. Large bodies of water in freezing modify the climate.

QUESTIONS

1. Describe some experiments illustrating changes of temperature produced by chemical action, by friction, and by dissolving a solid in a liquid.

2. Explain how it is that snow protects vegetation in winter. Will wrapping a thermometer in wool make it warmer? Why do woolen blankets keep the body warm?

3. How do large bodies of water modify the climate about them? Explain.

4. Why is it warmer in the center of a storm than in its outskirts?

5. Why does the skin feel cold when moistened with alcohol? Why does it feel cooler after being moistened with warm water than with cold water?

6. Why does a mixture of ice and salt freeze water?

7. Explain the use of double doors and windows in winter.

8. Why is it possible to hold one's hand in the steam coming from a locomotive boiler, when the temperature of the water inside the boiler may be far above 212° F.? How is it possible to raise water above 212° F.?

9. Explain how it is possible for fish to live all winter in the lakes of cold regions, where the thermometer falls below zero.

10. A liter of hydrogen gas weighs, at 0° and 76 centimeters, about .089 grams. Calculating from these data, in a certain quantitative experiment, one expected to obtain 200 cubic centimeters of hydrogen. How many cubic centimeters might actually have been collected when the thermometer stood at 20° C. and the barometer at 75 centimeters?

11. How many grams of lead will be needed to give off as much heat in cooling through 10° as will be given off by 100 grams of water in cooling through 10°?

12. If equal weights of water at 20° and mercury at 70° were poured together, what would be the resulting temperature?

13. Through how many degrees could 100 grams of water be heated by the amount of heat given off by the melting of 10 grams of ice? How many heat units would it take to change into steam the water formed by the melting of the ice?

Tables for Reference

To translate one thermometer scale into another.

$$C = \frac{5}{9}(F. - 32).$$
$$F = \frac{9}{5}C. + 32.$$

Boiling Points

Ether	37°
Alcohol	70°
Water	100°
Mercury	358°

Specific Heat

Copper	.095
Iron	.114
Lead	.031
Mercury	.033

Latent Heat of Vaporization

Ether	90
Alcohol	202
Water	537

Latent Heat of Fusion

Ice	80

Coefficients of Expansion (Linear)

Copper	.000017
Iron (cast)	.0000112
Iron (wrought)	.000012

Coefficient of Expansion (Cubical)

Gases	.00366

MAGNETISM AND ELECTRICITY

- A. MAGNETS.
  - I. *Natural and Artificial Magnets.*
    - Experiments 1, 2, 3, and 4.
  - II. *Induced Magnetism.*
    - Experiments 5, 6, and 7. Fig. 1.
  - III. *The Molecular Theory of Magnets.*
    - Experiments 8, 9, 10, and 11.
- B. STATIC ELECTRICITY.
  - I. *Two Kinds of Electrification.*
    - Experiments 12, 13, 14, and 15. Fig. 2.
  - II. *Conduction.*
    - Experiment 16. Fig. 3.
  - III. *Induction.*
    - Experiments 17, 18, and 19. Fig. 4.
  - IV. *Electrical Distribution.*
    - Experiments 20 and 21.
  - V. *Application of Principles.*
    - Experiments 22, 23, and 24.
- C. ELECTRIC CURRENTS.
  - I. *The Battery Cell.*
    - Experiments 25 and 26.
  - II. *To detect the Presence of an Electric Current and its Direction.*
    - Experiments 27 and 28.
  - III. *Some Effects of Electric Currents.*
    - A. Chemical Effects.
      - Experiments 29, 30, 31, and 32. Fig. 5.
    - B. Heating Effects.
      - Experiments 33 and 34.
    - C. Magnetic Effects.
      - Experiments 35, 36, 37, 38, 39, 40, and 41.
  - IV. *Electrical Measurements.*
    - Experiments 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, and 53.
  - V. *Induction.*
    - Experiments 54, 55, and 56.
  - Questions. Tables.

MAGNETISM AND ELECTRICITY

A. MAGNETS

I. Natural and Artificial Magnets.

EXPERIMENT 1.—Dip a piece of magnetite into iron filings. Find whether the filings cling to opposite parts.

EXPERIMENT 2.—Suspend the piece of magnetite. Note whether one part of it is inclined to point north.

EXPERIMENT 3.—Find a spot on the magnetite where iron filings cling most abundantly and lay this spot upon one end of a *steel* needle and draw it to the other end of the needle. Repeat this several times, always in the same direction. By means of the iron filings find whether the needle has become a magnet. Try the same experiment, using a piece of soft iron wire in place of the needle.

EXPERIMENT 4.—Having magnetized a needle, find out whether this needle will magnetize other needles.

II. Induced Magnetism.

EXPERIMENT 5.—While holding one end of a bar magnet near one end of a short rod of iron, test the power of the latter to lift iron filings. Remove the magnet. How is the iron affected?

EXPERIMENT 6.—Bring the horseshoe magnet near to a suspended rod of soft iron so that a pole of the magnet is underneath each end of the iron rod. Now by means of a bar magnet test the iron rod for polarity.

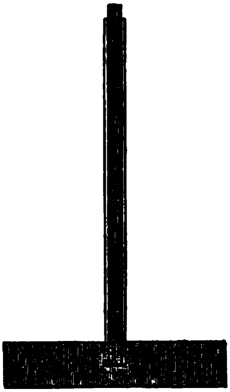

Fig. 1.

Experiment 7.—Support in a vertical position a glass tube about three inches long and one eighth of an inch internal diameter by fitting one end of it into a cork large enough to serve as a base. Fill the tube with pieces of soft iron wire of uniform size (say a quarter of an inch long). Find how many bits of iron each pole of a bar magnet will lift, and try the power of the magnet at various points between the poles. Lay a second bar magnet upon the first with like poles together and repeat the experiment. Repeat the experiment, having unlike poles together. Place one pole of a magnet upon the upper end of the glass tube and place the opposite pole of another magnet against the side of the tube an inch or two below the upper end. Try, now, the power of the upper magnet to lift bits of iron. Reverse the poles of the lower magnet and try again.

III. The Molecular Theory of Magnets.

Experiment 8.—Magnetize a sewing needle, present it to iron filings. Heat it red hot; now again test its magnetism by means of iron filings, or test it by means of the apparatus described in Experiment 7.

Experiment 9.—Magnetize a knitting needle, test its magnetism by the apparatus described in Experiment 7. Drop it upon the floor several times; now test its magnetism again.

Experiment 10.—Magnetize a sewing needle; test it for poles and a neutral point. Break it at the neutral point; test for new poles and neutral point. Break again at neutral point and test for new poles.

EXPERIMENT 11.—Place two bar magnets about an inch apart with like poles adjoining. Cover them with a piece of glass. Sprinkle fine iron filings thinly over the glass, tapping the glass occasionally to assist the filings in arranging themselves. Draw a sketch to illustrate the arrangement of the filings.

Repeat the experiment, placing *unlike* poles of the magnet adjoining each other. Repeat the experiment, using a horseshoe magnet instead of a bar magnet.

B. STATIC ELECTRICITY

I. Two Kinds of Electrification.

EXPERIMENT 12.—Make a stick of sealing wax slowly approach and touch a pith ball suspended upon a silk thread (Fig. 2). Now do the same after having rubbed the sealing wax with flannel. By sliding the silk thread make this pith ball slowly approach and touch another pith ball suspended in the same manner. Make the stick of sealing wax slowly approach and touch, if it will, each of the pith balls again. Be careful not to touch either of the pith balls with your hand during the exercise.

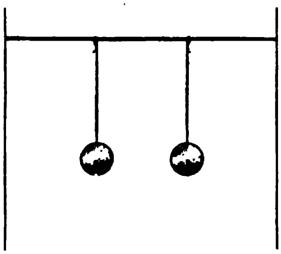

FIG. 2.

EXPERIMENT 13.—(Before beginning this exercise touch each pith ball with your hand to discharge any electricity which may have been left in it from the last exercise.) Repeat the foregoing exercise, using a glass tube and silk in place of the stick of sealing wax and flannel.

Experiment 14.—Discharge with the hand if necessary the two pith balls. Suspend them several inches apart. Electrify one by means of the sealing wax and the other by means of the glass tube. Now make the glass tube approach *but not touch* the first pith ball, and the stick of sealing wax approach *but not touch* the second pith ball. Also make the pith balls approach each other by sliding the silk threads.

Experiment 15.—Charge one pith ball positively and the other negatively. Rub the glass tube with a silk cap to which is attached a silk thread by means of which the cap may be drawn off the tube. Make the cap approach *but not touch* each pith ball in turn. Is the silk cap electrified? How? What is the proof?

Rub the stick of sealing wax with a flannel cap and by means of a silk thread attached to it make it approach *but not touch* each pith ball in turn. Is the flannel cap electrified? How? What is the proof?

II. Conduction.

Experiment 16.—Electrify a stick of sealing wax and touch it to the silk thread, *a b* (Fig. 3). Do the pith balls at either *e* or *f* separate? Slide the stick of sealing wax over to the copper wire, *b c*. Do the pith balls at either *e* or *f* separate now? (Those at *f* are suspended by copper wires and those at *e* are suspended by silk threads.)

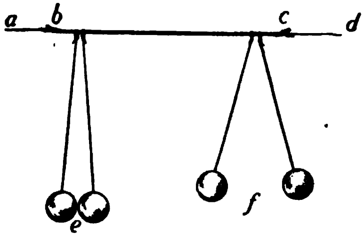

Fig. 3.

Moisten the silk threads which suspend the pith balls at *e*. Try now to conduct electricity to them by touching the copper wire, *b c*, with the electrified stick of sealing wax.

III. Induction.—The Influence of Electrified Bodies upon Neighboring Objects.

EXPERIMENT 17.—Bring an electrified stick of sealing wax underneath a pith ball, *e* (Fig. 4), suspended by a copper wire. Make the sealing wax approach very near to the pith ball, but do not allow it to touch. While holding the sealing wax near to *e*, lift the pith ball *f*, which is also suspended by a copper wire, off from the copper wire, *b c*, and hang it upon the silk thread, *c d*. A loose piece of silk thread, *g*, is provided, so that this may be done without touching the copper with the fingers. Test now each ball with both glass and sealing wax to determine whether it is positively or negatively electrified.

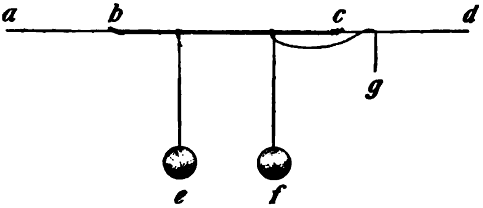

FIG. 4.

EXPERIMENT 18.—Hold an electrified stick of sealing wax near to but not touching a pith ball suspended by a silk thread. Touch the pith ball with the finger while it is near the sealing wax. Test now the pith ball with both glass and sealing wax to determine whether it is positively or negatively electrified.

EXPERIMENT 19.—Can you, by means of an electrified glass tube, charge a pith ball suspended upon a silk thread either positively or negatively at pleasure? Try it.

IV. **Electrical Distribution.**

EXPERIMENT 20.—Hold a glass tube by the hand placed midway between the two ends, and rub one end with silk. By means of a positively electrified pith ball determine whether the other end of the glass tube is also electrified. Explain.

EXPERIMENT 21.—Electrify, by touching it several times with an electrified glass tube, or the electrophorus, a small tin cup insulated upon a glass beaker. Test both the inner and outer surface of the cup by means of a positively electrified pith ball. Compare also the intensity of the charge in the handle with that upon the outer surface of the cup.

V. **Application of Principles.**

EXPERIMENT 22.—Use an electrophorus to charge a Leyden jar so that its outer coat shall be first positively charged, then negatively charged.

EXPERIMENT 23.—Pass ten or twenty sparks into a Leyden jar from an electrophorus and then discharge it through your body.

EXPERIMENT 24.—Light the gas by means of a spark from a Leyden jar.

C. ELECTRIC CURRENTS

I. **The Battery Cell.**

EXPERIMENT 25.—Dip a strip of zinc into dilute sulphuric acid (1 volume of acid to 20 volumes of water) in a tumbler. Note the bubbles of hydrogen which form upon its surface. Dip a strip of copper into the acid, and note that bubbles do *not* form upon its surface. Allow the ends of the strips which extend above the liquid to touch each other. Note that bubbles of gas now form also upon the strip of copper. Amalgamate the zinc with mercury.

Note that few, if any, hydrogen bubbles are now produced upon the surface of the zinc, but when the upper ends of the zinc and copper touch, hydrogen bubbles appear upon the latter. Drop sodium bichromate into the solution until hydrogen bubbles disappear from the copper strip. If the strips are allowed to remain in the acid with the upper ends connected, it will be found that the zinc wastes away while the copper remains undiminished. What are the essentials of a battery cell?

EXPERIMENT 26.—Examine a Samson or other cell and explain how it fulfills the essential requirements of a battery cell.

II. **To detect the Presence of an Electric Current and its Direction.**

EXPERIMENT 27.—Place a cell so that the carbon pole is due north of the zinc pole. Connect them by a short piece of copper wire, which will lie in the magnetic meridian. Hold a compass needle over this wire, and note in which direction its north-seeking pole is deflected. Hold the compass needle underneath the wire, and note in which direction the north-seeking pole is deflected. Do not leave the copper wire in circuit longer than is necessary.

EXPERIMENT 28.—From the data obtained in the previous experiment, determine by means of a compass needle in what direction an electric current is passing through a given wire.

III. **Some Effects of Electric Currents.**

A. *Chemical Effects*

EXPERIMENT 29.—Attach carbon terminals to the wire connected with a battery. Dip them into a solution of copper sulphate, not allowing them to touch each other. Notice what occurs on each electrode.

EXPERIMENT 30.—Pass an electric current through water in the apparatus provided for the electrolysis of water. Continue the operation until one of the tubes is full of gas. Note at this point how much gas the other tube contains. Test these gases for hydrogen and oxygen.

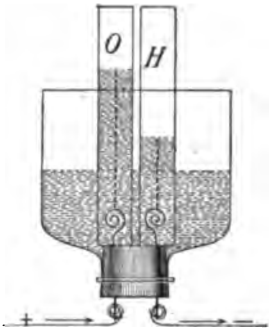

FIG. 5.—Electrolysis of water.

EXPERIMENT 31.—Spread upon a sheet of tin a piece of paper moistened in a solution of starch and potassium iodide. Press one terminal against the metal sheet, and with the other draw some characters upon the moistened paper. What evidence have you that the potassium iodide has been decomposed?

EXPERIMENT 32.—Repeat Exercise 29, and immediately after disconnecting the battery, place an electric bell in the circuit in its stead.

Storage batteries.

B. *Heating Effects*

EXPERIMENT 33.—Send the current through two or three inches of fine iron or German silver wire wound around the bulb of a thermometer or touching a cake of paraffin.

EXPERIMENT 34.—Connect the copper and the zinc of the cell used in Experiment 25. Take the temperature of the liquid, and while the zinc and copper remain connected note the behavior of the thermometer from time to time.

C. *Magnetic Effects*

Recall Experiments 27 and 28.

EXPERIMENT 35.—While passing a current through a small helix of wire, test it for magnetism by bringing it near to a magnetic needle.

EXPERIMENT 36.—Place an iron core inside the helix and close the circuit. For evidence that the iron core is magnetized, present it to some bits of iron.

EXPERIMENT 37.—Label one end of the helix *n*, and decide which end of the wire must be connected with the positive pole of a battery. Send the electric current through the helix, and by means of the compass needle determine whether your prediction is correct. Record your prediction before the experiment, and the result afterward. Place the iron core inside the helix and repeat the experiment. (The end of the helix around which the current is passing *opposite* to the hands of a watch is the *north* pole. The end around which it is passing *with* the hands of a watch is the *south* pole.)

EXPERIMENT 38.—Examine and trace the path of the current through a telegraph sounder.

EXPERIMENT 39.—Examine an electric bell and trace the path of the current through it. Send the current through it so as to make a "single-stroke" bell; a "clatter" bell. Illustrate by diagrams.

EXPERIMENT 40.—Trace the path of the current through an electric motor.

EXPERIMENT 41.—Examine and explain the tangent galvanometer.

IV. **Electrical Measurements.**

In all measurements where a tangent galvanometer is used, throw in enough extra resistance to bring the deflection of the needle below 45°. Slight changes in resistance will then be more readily detected by the needle. Why is this true?

EXPERIMENT 42.—Measure by means of a micro-caliper the diameter of each of the specimens of wire furnished you, and determine its number by referring to the table on page 78. Test your result by using a wire gauge.

EXPERIMENT 43.—Find the resistance, and from that calculate the length of wire on each of several spools containing wire of known number and known material. Proceed in the following manner: Pass a current from a single cell through each spool in turn, connecting the spool, a galvanometer (tangent), and a resistance box in series. By means of the latter introduce enough extra resistance to bring the deflection of the needle to a point below 45°. Note the deflection. Remove the spool from the circuit, and the galvanometer needle will be deflected more than when the spool was in circuit. Add resistance enough to send the needle back to its former deflection, and the amount of resistance added will be that offered by the wire upon the spool.

Suppose it were found that the wire (known to be copper No. 24) on one spool offered 0.5 ohms resistance. Then, as resistance varies as the length (see text-book for laws of resistance), and as it takes 39 feet of No. 24 copper wire to offer a resistance of 1 ohm (see data on page 77), it must take 0.5 of 39 feet to offer 0.5 ohms resistance.

EXPERIMENT 44.—Calculate the resistance of your galvanometer, containing wire of known number and material. Measure the diameter of the coil, and from that compute the length of the number of turns of wire (see data on page 77).

Suppose the wire were No. 22 (diameter 25), and that the length of wire were found to be 24 feet. Then as resistance varies inversely as the square of the diameter, and as it takes 39 feet of No. 24 copper wire (diameter 20) to offer a resistance of 1 ohm, it is obvious that it will take $\frac{25^2}{20^2}$ of 39 feet of No. 22 wire to offer a resistance of 1 ohm, or about 60 feet. Then 24 feet of this wire will offer $\frac{24}{60}$ of 1 ohm, or about 0.4 of an ohm resistance. Test the calculated result by sending a current through the galvanometer connected with another galvanometer. Treat the first galvanometer as though it were one of the spools in Experiment 43, and find its resistance. Compare this result with the calculated result.

Experiment 45.—Find the internal resistance of your battery cell by connecting it with the galvanometer and a known amount of extra resistance (say 2 ohms), and noting the deflection of the needle. Refer to the table of tangents (page 78), and find what deflection of the needle indicates one half the current that is now passing. Add resistance until the needle is deflected to this point. If the current has been decreased to one half, the resistance has been doubled.

For example:

Let x = internal resistance of cell.
" .4 = resistance of galvanometer.
Let 2 ohms = extra added resistance.

Then suppose $x + .4 + 2$ deflects galvanometer to 45°.

Tangent of 45° = 1.000.
$\frac{1}{2}$ " " " = 0.500.

Deflection represented by tangent .5 = 27°.
Now add resistance, and suppose

$x + .4 + 2 + 2.6$ deflects galvanometer to 27°.

Then

$$x + .4 + 2 = 2.6$$
$$x = 2.6 - 2.4$$
$$x = .2 = \text{internal resistance of battery cell.}$$

Experiment 46.—By comparing with some standard, find how much your galvanometer needle is deflected for 1 ampère of current, then by referring to the table of tangents make a table showing what strength of current is indicated by the deflection of your needle for each degree from 85° to 36° when fifteen turns of wire are used upon your galvanometer; also when five turns are used.

Experiment 47.—Make a table showing the electromotive force of your cell in each of the following cases: Use 15 turns of wire; close the circuit through the galvanometer alone; add half an ohm of resistance, add one ohm, add 2, 3, 4, etc., to 10 ohms. Does the E. M. F. vary with the resistance?

From Ohm's law:

$$C = \frac{E}{R}, \text{ therefore } E = R\,C.$$

Experiment 48.—Connect your cell with the voltmeter instead of the galvanometer, adding from 0 to 10 ohms of resistance, and notice whether the E. M. F. varies.

Experiment 49.—Choose two cells which are as nearly alike as possible in E. M. F. Connect them in series and first calculate as nearly as you can the amount of current which they will send through 5 turns of wire on the galvanometer and 2 ohms of added resistance, then close the circuit and find how the result compares with your estimate.

Series arrangement:

$$\frac{(\text{E. M. F.}) \times (\text{Number of Cells})}{(\text{Internal Resistance}) \times (\text{Number of Cells}) + \text{External Resistance}}$$

EXPERIMENT 50.—Connect the cells in parallel and repeat the foregoing exercise, with the exception of the calculation, which it will not be necessary to make, unless the cells are alike in E. M. F. and internal resistance.

Parallel arrangement:

$$\frac{\text{E. M. F.}}{\dfrac{\text{Internal Resistance}}{\text{Number of Cells}} + \text{External Resistance}}$$

EXPERIMENT 51.—Use the ammeter in place of the galvanometer and find out whether these two cells send more current through it when connected in series or in parallel.

(*a*) Without added resistance.

(*b*) With added resistance of 0.5 ohms.

EXPERIMENT 52.—Find about what current is required to operate the pieces of apparatus furnished you. (Electric bell, small motor, electrolysis apparatus, etc.) Knowing the E. M. F. and internal resistance of your cell, the resistance of the galvanometer, and the amount of current indicated by the deflection of the needle, calculate the resistance of the apparatus used. What arrangement of battery is desirable?

EXPERIMENT 53.—Connect two motors with a rubber band. Operate one with a battery and connect the other with the galvanometer to see whether it is producing a current as a dynamo. If so, how much? What is its electro-motive force? How much current is used in the first motor?

V. **Induction.**

EXPERIMENT 54.—Examine and explain the telephone.

EXPERIMENT 55.—Examine and explain the magneto-electric machine used for telephone calls.

EXPERIMENT 56.—Operate the hand dynamo and see whether it goes harder when its current is made to do work, such as decomposing water, heating a wire, ringing a bell, operating a motor, etc.

QUESTIONS

1. How would you distinguish between a *magnetic substance* and a *magnet?*

2. Why do iron filings cling only to the ends of a needle that has been made a magnet?

3. How is it possible to charge a pith ball positively by using sealing wax and flannel?

4. Upon what does the electro-motive force of a battery cell depend? Upon what does the quantity of a current depend?

5. What is meant by polarization? What means are taken to prevent it? Why is it necessary to prevent it?

6. In the process of electroplating, to what pole is it necessary to connect the object to be plated? Why?

7. By means of a compass needle, how would you detect the direction of a current through a wire?

8. A certain spool containing copper wire No. 24 offers a resistance of 0.2 ohms. What is the length of wire on the spool? How much current would a battery cell with an internal resistance of 0.1 ohm and an E. M. F. of 0.8 volts send through this spool?

9. Why is a "series" arrangement of batteries generally desirable? When would a "parallel" arrangement furnish more current?

DATA

39 feet of No. 24 copper wire offers 1 ohm resistance.

Resistance is proportional to length.

Resistance is inversely proportional to the square of the diameter of a wire. Diameter of No. 24 wire is twice that of No. 30 wire, therefore its resistance is one quarter as great.

The resistance of platinum is 6.30 times that of copper, while the resistance of iron is 6.62 and that of German silver is 12.28 times that of copper.

TABLE OF DIAMETER OF WIRE

Diameter of No. 12 is 80 thousandths of an inch.
13—72
14—64
15—57
16—51
17—45
18—40
19—36
20—32
21—28
22—25

Diameter of No. 23 is 23 thousandths of an inch.
24—20
25—18
26—16
27—14
28—13
29—11
30—10

TABLE OF TANGENTS

Deg.	Tan.	Deg.	Tan.	Deg.	Tan.
1	.02	31	.60	61	1.80
2	.04	32	.63	62	1.88
3	.05	33	.65	63	1.96
4	.07	34	.68	64	2.05
5	.09	35	.70	65	2.15
6	.11	36	.73	66	2.25
7	.12	37	.75	67	2.36
8	.14	38	.78	68	2.48
9	.16	39	.81	69	2.61
10	.18	40	.84	70	2.75
11	.19	41	.87	71	2.90
12	.21	42	.90	72	3.08
13	.23	43	.93	73	3.27
14	.25	44	.97	74	3.49
15	.27	45	1.00	75	3.73
16	.29	46	1.03	76	4.01
17	.31	47	1.07	77	4.33
18	.33	48	1.11	78	4.71
19	.34	49	1.15	79	5.15
20	.36	50	1.19	80	5.67
21	.38	51	1.24	81	6.31
22	.40	52	1.28	82	7.12
23	.42	53	1.33	83	8.14
24	.45	54	1.38	84	9.51
25	.47	55	1.43	85	11.43
26	.49	56	1.48	86	14.30
27	.51	57	1.54	87	19.08
28	.53	58	1.60	88	28.64
29	.55	59	1.66	89	57.29
30	.58	60	1.73	90	Inf.

LIGHT

I. LIGHT IN STRAIGHT LINES.
  Law of Inverse Squares.
    Experiments 1 and 1a. Fig. 1.
  Visual Angle.
    Fig. 2.
  Light through Small Apertures.
    Experiment 2. Fig. 3.
  Shadows.
    Experiment 3 and Exercise 4. Fig. 4.

II. REFLECTION OF LIGHT.
  Plane Mirrors.
    Experiment 5, and Exercises 6, 7, and 8. Figs. 5, 6, 7, 8, and 9.
  Curved Mirrors.
    Experiment 9, and Exercises 10, 11, 12, and 13. Figs. 10, 11, and 12.
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III. REFRACTION OF LIGHT.
  Index of Refraction.
    Experiment 14. Fig. 14.
  Enlarged Images by Refraction.
    Experiment 15.
  Lenses.
    Experiments 16, 17, 18, 19, 20, and 21. Fig. 16.
  The Spectrum.
    Experiment 22.

I. LIGHT IN STRAIGHT LINES*

Law of Inverse Squares.

EXPERIMENT 1.—Place a cardboard, *X*, having in it a hole which is either a square 1 inch in diameter, a circle 1 inch in diameter, or a triangle 1 inch on a side, 2 inches in front of a candle flame. Place a screen whose surface is ruled in square inches, 2 inches, 4 inches, and 6 inches behind *X*. Notice how large a portion of the screen is illuminated in each case. Note also the shape of the patch of light. Draw to a scale the square pyramid, the triangular pyramid, or the cone of light to illustrate your experiment. (See Fig. 1.)

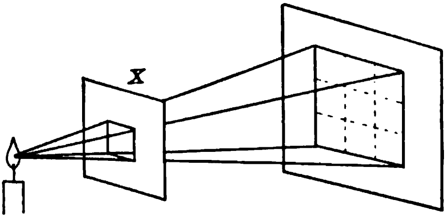

FIG. 1.

It must be remembered that light is going out from the candle flame in all directions, but we are considering only those rays which get through the opening in *X*.

What must be the relative intensity of the illumination when the screen is held directly behind *X*, 2 inches behind *X*, 4 inches behind *X*?

Where would it be necessary to place one candle in order that it should give as much light as four candles? Test your prediction by an experiment.

What would be the candle power of a light which gives as much illumination at a distance of 20 feet as a candle does at 1 foot?

If an observer were sitting 90 feet from a stage, how large a portion of it would be obscured from him by an object 6 inches broad 3 feet in front of him?

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* Considerable portions of this chapter on light have been taken from Woodhull's First Course in Science, with the permission of the publishers, Messrs. Henry Holt & Co. (New York).

Experiment 1a.—Repeat Experiment 1, using sunlight in place of the candle, and varying the distance of the screen behind *X*. Try holding the screen several feet back of *X*. Do the rays of sunlight diverge as the rays of light from the candle flame? Why?

Visual Angle.

In Fig. 2, *m* and *n* represent the upper and lower ends of an object. The angle which the line of light *m e* and *n e* make at the eye, *e*, is called the visual angle. Large objects near to the eye subtend a large visual angle. Large objects far from the eye subtend a small visual angle. How does this help us to estimate the size of an object by its distance from us, and the distance of an object from us by its size?

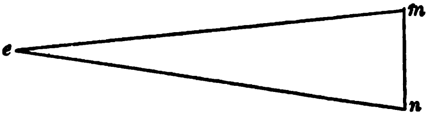

Fig. 2.

The moon is about 240,000 miles distant from the earth and the sun about 92,500,000 miles, but they both subtend for us about the same visual angle. How must their diameters compare with each other?

If in Fig. 2 the lines *e m* and *e n* diverged at the rate of 1 mile in every 114, they would be as far apart as the distance across the moon if extended to the moon. What must be the moon's diameter if it is 240,000 miles distant? What must be the diameter of the sun if it is 92,500,000 miles away, and subtends the same visual angle as the moon?

Light through Small Apertures.

EXPERIMENT 2.—Substitute for cardboard *X*, used in Experiment 1, a cardboard having in it a hole about 0.1 inch in diameter. Hold this about 1 inch from the candle flame, and holding the screen directly behind the cardboard, move it slowly away from it to a distance of about 4 or 5 inches, until a distinct image of the candle flame appears upon the screen. Why is it inverted? Why is it enlarged? (Refer to Fig. 3.)

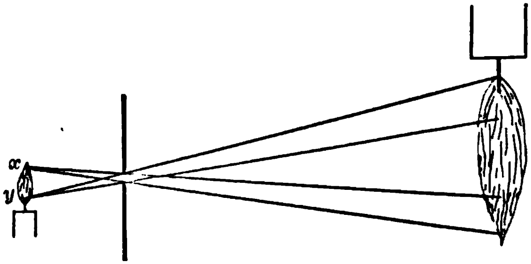

FIG. 3.

What portion of the screen is lighted by the point *x*? By the point *y*? It must be remembered that we are considering only so much of the light from the point *x* as goes through the opening. Why is it not possible to see around a corner?

Images through keyholes.
Cameras.

Shadows.

EXPERIMENT 3.—Repeat Experiment 1, substituting for cardboard *X* the square, circle, or triangle cut from its center. Fig. 4 represents the case in which the square, *c d*, was held 2 inches from the candle flame, and the screen 2 inches behind the square; *a b* represents the candle flame, whose length is estimated to be 1 inch.

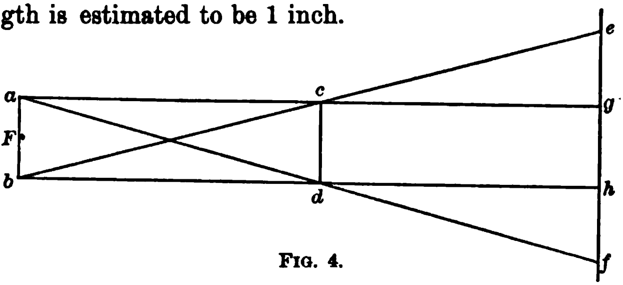

FIG. 4.

What portion of the screen receives no light from the flame? This is called the umbra. What portion receives no light from *a*? From *b*? What about the portions *e g* and *f h*? They are called the penumbra. What about the portions above *e* and below *f*?

What must be the length of the portions *e g*, *g h*, and *h f*?

Suppose the candle flame were reduced to the point *F*, what would be true of the umbra and penumbra?

Shadows cast by electric lights.

What would be the effect on the umbra and penumbra of moving *c d* nearer to or farther from the source of light?

EXERCISE 4.—Draw a figure similar to Fig. 4 to represent the shape of the umbra and penumbra when the source of light is *larger* than the object casting the shadow. Make the candle flame 1 inch long and the object 0.6 inch.

What must be the shape of the moon's and the earth's shadows as cast by the sun?

About how long must their shadows be if the diameter of the sun is 860,000 miles?

Eclipses.

II. REFLECTION OF LIGHT

Plane Mirrors.

EXPERIMENT 5. PART 1.—Fig. 5 represents a piece of bright tin or nickel, which may serve for a mirror; *c d* is a scratch on its face perpendicular to *a b*, its base. Set the mirror on a blank page and draw a line along its base, marking the point *d* where the line *c d* touches the paper. Draw a perpendicular, *d g*, from the point *d*, and extend it about 2 inches.

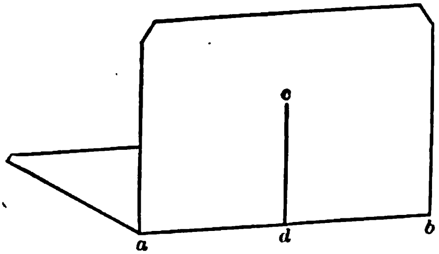

FIG. 5.

Referring to Fig. 6, set up a small object (a pin is convenient) as nearly vertical as possible at any point (*1*) outside of the line *d g*. Place the eye on a level with the paper, and in such a position that the image of this pin shall appear behind the mirror exactly in line with *d*, and set up a second pin in front of the eye so as to appear exactly in line with the image of the first pin and with *d*. Remove the mirror and draw lines from *d* to pins (*1*) and (*2*). Extend each of these lines to exactly the same length, say two inches, and place the letters *f* and *e* at their extremities.

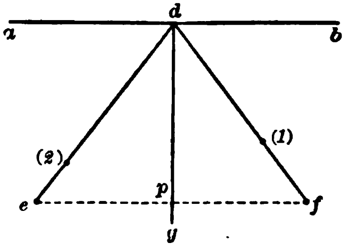

FIG. 6.

Measure as accurately as possible the distance each of these lines has departed from the perpendicular at these points. Record the results after the following manner, calling the distance of *f* from the perpendicular *f p*, and that of *e* from the perpendicular *e p*:

$$\frac{fp}{ep} = \frac{1.65}{1.625} = 1.015 + \text{(a supposed case).}$$

The angle subtended by *fp* is called the angle of incident, and that subtended by *ep* is called the angle of reflection. Measure these angles in degrees with a protractor. Repeat the observations and measurements a number of times, changing the positions of the pins each time; average the results, and if you discover any fixed ratio between the angles of incident and reflection, state it as a law.

Part 2.—Make a general statement describing the position which an image seen in a mirror appears to occupy with reference to the position which the object actually occupies.

Test your conclusion, which you should look upon as only an hypothesis until it has been tested, by replacing the mirror and pin (*1*) to the first position, and place the eye so that the image of the pin shall be seen in the mirror a little one side of the line *c d*. Hold the eye rigidly in position and make two or three pin-pricks upon the page between the eye and the mirror to mark the direction from the eye to the position of the image (*1′*). Repeat this for two or three positions. Remove the mirror and draw lines through the pin-pricks to *a b* and extend them in the same direction behind the mirror by dotted lines. Do these all pass through the same point behind the mirror? So long as the object (*1*) remains stationary, however much the eye may move, does the position of the image (*1′*) remain fixed?

Exercise 6.—Applying the principle which you have just laid down, complete the diagram (Fig. 7) without the aid of the mirror or pins, showing where the image of the object *m n* would appear behind the mirror *a b* when the eye is stationed at *e*. Draw the lines of light from the extremities *m* and *n* of the object to the eye, *e*, showing at what points they are reflected from the mirror. Represent the angles of incident and reflection made by each ray of light. Extend the lines of vision to the extremities *m′* and *n′* of the image.

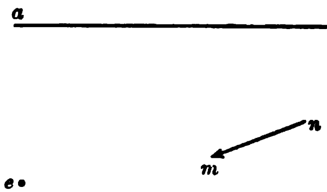

Fig. 7.

Having drawn the figure as you think it ought to be, test its correctness by using the mirror and an object and applying them to the figure; in which case, of course, it will be impossible to put the eye at *e*, but it may be put farther back in the direction of *n′ e*, and when it is found what position the image of the point *n* occupies, the eye may be moved so as to look in the direction *e m′*, and thus the position which the image of the point *m* occupies may be found. Pins may be set up at *m* and *n* to represent the extremities of an imaginary object, or a sliver of wood may be cut the proper length and laid upon the figure *m n*.

Does the image of an object seen in a mirror appear to be inverted or reversed? Try holding a printed page before a mirror.

EXERCISE 7.—Suppose you live at *e* (Fig. 8), and across the street at *a b* is a show window which serves as a mirror; *m n* is a street car passing up the avenue. Complete this diagram, showing where the image *m′ n′* will appear to be

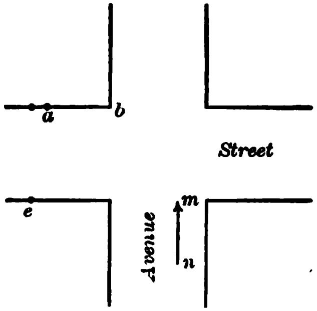

FIG. 8.

located, and showing the direction in which the image will appear to be moving.

Where must a placard be hung upon the show window to hide the point *n* from your vision?

Exercise 8.—*m n* (Fig. 9) represents a lead pencil which you hold in your mouth so that an end projects on either side; *e* represents the position of one of your eyes, the other being closed meanwhile; *a b* is a mirror in which you see the image of the lead pencil. The purpose of holding it in your mouth is to insure that it shall be about the same distance as your eye from the mirror while you are taking the observation. Cut a strip of paper just long enough to hide the image of the pencil when laid upon the mirror.

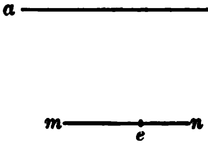

Fig. 9.

What difference would it make in the result if your eye were nearer to or farther from the mirror than the pencil was? Try it by tipping your head back and forth while performing the experiment.

How long and broad must a hand mirror be to just show your whole face?

What is the shortest mirror in which you may see your whole person?

Does your distance from the mirror make any difference with the result?

Curved Mirrors.

EXPERIMENT 9.—Repeat part 1 of Experiment 5, using a strip of tin, nickel, or other bright metal, curved so as to form the arc of a circle with a radius of about 6 inches. Try both the concave and convex side of the mirror. State whether the ratio between the angle of incident and reflection is the same for curved as for plane mirrors.

EXERCISE 10.—Suppose $c\ c'''$ (Fig. 10) is the arc of a circle of which d is the center, and the curved mirror is placed upon this arc, an object is placed at $m\ n$ and the eye at e. The ray of light from m is reflected to the eye at the point c, that from o at c', from p at c'', and from n at c'''. Complete the diagram, making it show the position of the image $m'\ o'\ p'\ n'$, its shape and its size; also the angles of incident and reflection for each of the four rays. Measure these angles with your protractor to determine whether the figure is correct. Test the truth of your conclusion by holding the curved mirror before your face and bringing a small object, $m\ n$, between your face and the mirror.

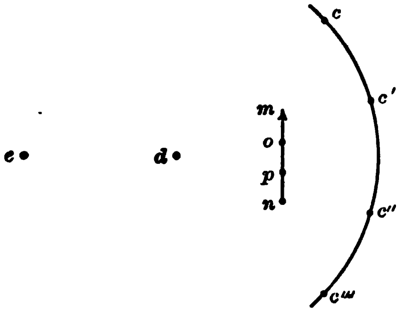

FIG. 10.

Exercise 11.—Turn the mirror about, using still the concave side, so that the plane of the curve shall be vertical, and moving it to and fro before the face, watch the changes in your image continually. Let *m n* (Fig. 11) represent a vertical line across the face, *e* the position of the eye, *a b* the mirror, *d* the center of the curve, and *c* and *c′* the places upon the mirror where the rays of light from the points *m* and *n*, respectively, are reflected to the eye. Complete the diagram, showing, by lines, the courses which rays of light from *m* and *n* must take in order to reach the eye by reflection from the mirror, showing also the position and relative size of the image *m′ n′*.

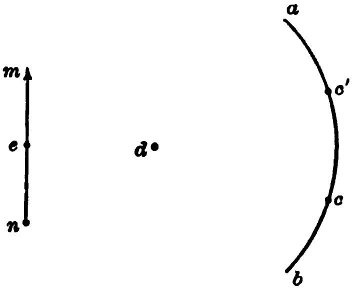

Fig. 11.

The mirror, as you have just used it, was curved vertically, but straight horizontally. Does it give a direct or an inverted image? When near to or far from the face? Does it give an enlarged or a diminished image? Is the image affected horizontally in the same way as it is vertically? Suppose it were concave in all directions like a portion of the shell of a sphere—i. e., like a lamp reflector—in what respect would it give different images from those you have just obtained? Try it with a lamp reflector.

EXERCISE 12.—Turn the convex side of the tin mirror used in the previous exercises toward your face with the plane of curvature vertical. Move it to and fro, noting as before changes in the appearance of the image. Complete diagram 12, in which *m n* represents a vertical line across the face, *e* the eye, *a b* the mirror, *d* the center of curvature, *c* and *c′* the places upon the mirror where the rays of light from the points *m* and *n*, respectively, are reflected to the eye. Show by lines the courses which rays of light from *m* and *n* take in order to reach the eye by reflection from the mirror. Show also the position and relative size of the image *m′ n′*.

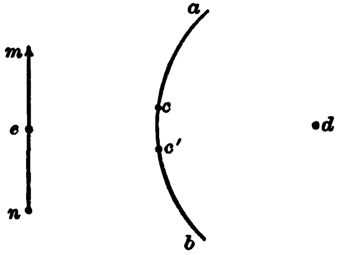

FIG. 12.

Does the mirror as you have just used it give a direct or an inverted image? An enlarged or a diminished image? Is it affected horizontally in the same way as it is vertically? Suppose it were convex in all directions like the back side of the lamp reflector, in what respect would it give different images than those you have just obtained? Examine your face in the bowl of a bright silver spoon, using both the concave and convex surfaces. Why does the image of your face appear long and narrow, or short and broad, as the case may be? When does the image of a straight object appear curved as seen in a curved mirror?

Exercise 13.—Place the curved mirror upon a sheet of white paper, and place a lighted candle upon the concave side of it about 6 or 8 inches distant from it. If the candle is a little taller than the mirror, so much the better. Note how the rays of light upon the paper converge to a point. Note the effect of moving the candle nearer the mirror.

Phases of the Moon.

From what does the moon get its light? Can an object be seen at all unless it either reflects or produces light?

Explain by a diagram the phases of the moon. Designate it as Fig. 13.

III. REFRACTION OF LIGHT

Index of Refraction.

Experiment 14.—Fig. 14 represents the base of a glass cube, such as is used for paper weights; *a* and *o* represent the points where scratches on the face of the cube touch the paper; *b o* is drawn through *o* perpendicular to the opposite sides of the diagram.

Place such a cube in the middle of a blank page, draw the outline around its base, and mark the points *a* and *o*. Remove the cube and draw the perpendicular *b o*, and extend it to a point *d*, so that *o d* shall at least be as long as *o b*. Replace the cube, taking great care to make the lines *a* and *o*, which are drawn upon the glass, stand exactly over the points so marked upon the diagram. Set a pin vertically at *b* and another at any point upon the line *o d*, and place the eye behind it on a level with the plane of the paper. If the apparatus and the drawing are correct, this pin, the line *o*,

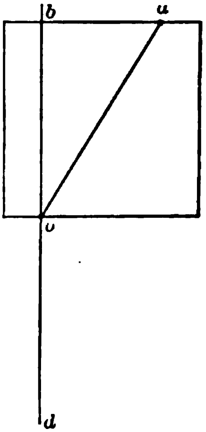

Fig. 14.

and the pin *b*, will be seen to be exactly in a straight line. Place the eye in such a position that *a* shall seem to be exactly behind *o*. While the eye is held rigidly in line with *a* and *o*, place a pin in front of it to mark the direction from *o* to the eye. Remove the cube and draw a line from *a* to *o* and from *o* to the pin, and extend this latter line so as to make it exactly equal to *a o*. Mark the extremity of it *e*.

What does the line *a o e* as it appears upon your diagram indicate about the ray of light which passed from *a* to your eye? This is refraction. Was the ray of light which passed in the direction *b o d* refracted? Note that the line *b o d* is perpendicular, and the line *a o* is oblique to the side of the cube. Measure with great care the perpendicular distance from *e* to the line *o d*. Call this *e p*. Also measure the distance from *a* to *b*. Compare these two measurements to find out how much more the line *o e* diverges from the perpendicular *b d* than the line *o a* does. Express it as follows:

$$\frac{ep}{ab} = \frac{\cdots\cdot}{\cdots\cdot} = \cdots\cdot$$

Your measurements will furnish figures to take the places of the dots. This furnishes a means of telling how much a ray of light is bent in passing from one medium into another obliquely to the surface between the two, and is therefore called the *index of refraction*. It differs with different media.

Place a dot a short distance from the cube beyond *a*, where you think a ray of light would pass in taking the course *a o e*. Mark the dot *g*. Then test your conclusion by replacing the cube, putting pins at *g* and *e*, and sighting through to see whether the four points *g*, *a*, *o*, and *e* appear in a straight line. If the position which you first chose for *g* is found not to be correct, mark it g', and mark the position which you select for trial g''.

Measure the index of refraction for the ray *g a o* at *a*. Record the results as before.

Formulate a law for the refraction of light as it passes obliquely from air into glass.

Enlarged Images by Refraction.

Experiment 15.—Cut a small strip of paper four tenths of an inch wide. Moisten it and stick it lengthwise upon the face of a prism. Let the lower end of the strip of paper extend to the lower end of the prism. Place the prism on end, having the face, marked by the strip of paper, toward the top of the page. Draw an outline around the prism and put dots, *m* and *n*, at the points where the vertical edges of the strip of paper meet the page. Place the eye at the bottom of the page so that *m* shall be seen through one and *n* through the other of the remaining faces. Hold the eye rigidly in position, and make two or three pin-pricks upon the page to mark the path which the ray of light takes in passing from *m* to the eye, and likewise two or three to mark the path of the ray from *n* to the eye. Estimate the width of the strip of paper as seen thus through the prism, and record your estimate. Remove the prism and draw lines from the bottom of the page through the pin-pricks to the outline of the prism, and then to the points *m* and *n* to represent the lines of light. Extend the lines which were drawn from the bottom of the page to the prism, straight through the diagram to the opposite side of it, and mark their extremities m' and n'. These latter should be dotted lines, to indicate that they represent the *apparent* path which the rays of light took in passing from *m* and *n* to the eye. Measure very carefully the distance $m'n'$. How does it compare with your estimate? Compare it with the distance mn thus:

$$\frac{m'n'}{mn} = \frac{\cdots\cdot}{\cdots\cdot} = \cdots\cdot$$

How many times was the object magnified? Designate this diagram as Fig. 15.

Lenses.

EXPERIMENT 16.—*To illustrate how reversed, as well as enlarged images may be produced by refraction.* Use a cylinder of glass about two inches in diameter, or a round bottle containing water. Fig. 16 represents the base of the cylinder which is to be outlined upon a blank page, and the points *a* and *b* represent where lines drawn upon the glass touch the paper. Draw the line *a b*, and through its middle point draw the line *x y* perpendicular to *a b*. Extend it several inches on either side of the diagram. Set up pins at *x* and *y*, and place the eye in such a position that *y* shall appear to be exactly behind *x*. While holding the eye rigidly in this position, make two pin-pricks between the cylinder and the eye to mark the path which the ray of light takes in coming from *b* through the cylinder and then to the eye; also two pin-pricks to mark the path of the ray of light which comes from *a* to the eye. Also make a pin-prick behind the cylinder to mark the path of the ray *e b* beyond *b*, and one to mark *e a* beyond *a*.

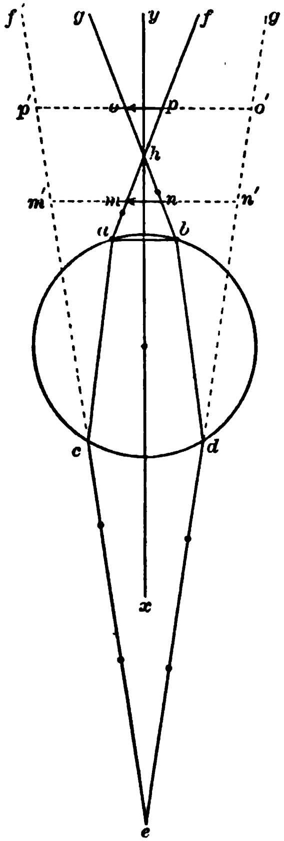

FIG. 16.

Remove the cylinder and draw a line through the pin-pricks from the bottom of the page to the diagram, then to *a* and then through the pin-prick behind *a*. In the same manner draw the line *e d b g*. Note how refraction causes the rays to cross each other beyond the cylinder, or lens. Set up an object at *m n* and see if it appears to extend to *m′ n′* when seen through the lens. Remove the same object to the position *o p*. Does it appear inverted and enlarged as *o′ p′*? If the object is moved nearer to the lens than *m n* or farther from it than *o p*, it does not appear as large. Why? How does it behave in various positions between *m n* and *o p*? Why?

How would you determine the amount of refraction of these rays of light at the points *a*, *b*, *c*, and *d*?

Does this cylinder when in the upright position magnify vertically as well as horizontally? Try it.

The point *h*, where the lines *a m* and *b n* intersect, may be called a focus, and the position which the eye occupied —i. e., the point where these lines of light intersect upon the other side of the bottle—may be called a focus also. How would it affect the position of the focus *h* if the focus *e* were moved nearer to or farther from the bottle? Try it. Foci that are thus the companions of each other are called conjugate foci.

What is a principal focus?

Experiment 17.—Fill a bottle full of water, cork it, and hold it in the sunlight. Hold a screen a short distance behind it. Is the light converged to a point or a band? Why?

Experiment 18.—Examine a lens furnished you and predict how it will converge rays of sunlight. Try it.

Measure the distance of the principal focus from your lens. Record it.

Experiment 19.—Beat together two blackboard erasers in the sunlight, so as to produce a cloud of dust and hold your lens in it. Note how the lens affects the rays of light.

EXPERIMENT 20.—Place a screen facing a window of the room, and on the side of it toward the window your lens at its focal distance. Note a clearly defined picture of objects outside. Place a lighted candle and the lens on the side of the screen which is turned away from the window. Move the lens back and forth until a clearly defined picture of the candle flame is seen upon the screen. Move the candle nearer to the lens. How does it affect the focal distance?

Draw a diagram to illustrate how a lens forms a picture. Call it Fig. 17.

EXPERIMENT 21.—Put a drop of water upon a window pane. Look through it for a picture of the outside world. If the sun is shining upon it, hold a piece of paper behind it and find its focus for sunlight. Similar illustrations can be found in fish globes and in the globes used in drug-store windows.

The Spectrum.

To illustrate that light is composed of various colored rays, all of which have different indices of refraction, and hence may be separated by the prism.

EXPERIMENT 22.—Hold your prism in the sunlight so that its longest axis shall be horizontal and at right angles with the rays of sunlight. Let the further wall of the ceiling of the room act as a screen. Try holding the cardboard screen near the prism. Why is the result so different in the two cases? The patch of light of various colors which is seen upon the wall is called the *spectrum*. Which color is refracted least? Name as many of the colors as you can detect in the order of their refraction.

Place a second prism against the first. What effect has it upon the spectrum? Why? Does the sunlight pass through both prisms? See if you can catch it upon the cardboard screen. Can you use a second prism to disperse still farther the rays which pass through the first prism?

Draw a diagram to illustrate how sunlight is broken in passing through a prism. Call it Fig. 18.

QUESTIONS

1. Looking out over a landscape, a schoolhouse which was 75 feet high was found to subtend the same angle as a stick 1.5 inches long at a distance of 10 inches from the eye. A tree standing beside the schoolhouse subtended the same angle as the stick held 20 inches from the eye. How far away was the schoolhouse? How tall was the tree?

2. Which would give a better light for reading, a ten-candle-power lamp 3 feet from a book, or two gas jets each twenty-candle power 8 feet from the book?

3. Why are the images of trees and of other objects seen in the water always inverted?

4. Why is it impossible to have an inverted image of your face in a *convex* mirror? Under what conditions does the image of a straight object appear curved in either concave or convex mirrors?

5. When you look into the bowl of a silver spoon why do you never see a direct image of your face? Why is it always a diminished image?

6. How is the focus of a curved mirror changed by a change in the position of the source of light?

7. Why was it that in our experiments with the prism the spectrum appeared only in the last?

SOUND

I. How Sound is produced.
  Experiments 1, 2, 3, and 4.
II. How Sound is transmitted.
  Experiments 5, 7, 8, and 9. Exercise 6. Fig. 1.
III. Reflection of Sound—Echoes.
  Exercise 10.
IV. Intensity of Sound and Amplitude of Vibration.
  Experiment 11.
V. Resonators.
  Experiments 12 and 13. Fig. 2.
VI. Pitch.
  Experiments 14 and 15. Exercise 16. Fig. 3.
VII. Sympathetic Vibrations.
  Experiment 17.
VIII. Vibration of Strings.
  Experiment 18.
IX. The Musical Scale.
  Exercise 19.
Questions.

I. How Sound is produced.

All sound-producing instruments are in a state of vibration and cause vibration in the air.

Experiment 1.—Strike a tuning fork, and while it is still producing sound, touch the prongs to the surface of water in a tumbler; touch them to the tip of your tongue; touch them to the edge of an *empty* tumbler.

Experiment 2.—Bring a pith ball against a piano string while it is sounding; against the rim of a bell while it is sounding.

Experiment 3.—Blow through an organ pipe while holding it near the end of a long glass tube containing cork dust.

Experiment 4.—Strike a bell while holding it a few inches above a diaphragm upon which cork dust has been sprinkled.

Tremor of buildings due to vibrations of large organs.

II. How Sound is transmitted.

In order that sound may be heard, air or some medium must extend all the way from the sounding body to the ear.

Experiment 5.—Ring an electric buzzer, suspended in a bottle (Fig. 1); exhaust the air, and ring again; allow the air to enter, and ring again; pour in some ether, and after it has evaporated ring again; fill the bottle with hydrogen, and ring again. In which case was the sound most distinctly heard? In which case *least* distinctly?

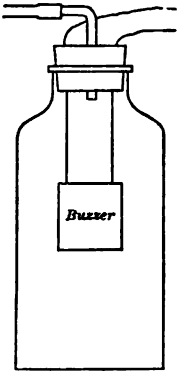

Fig. 1.

Exercise 6.—Compare the density of air with that of ether and hydrogen. Predict what would be the effect of ringing the buzzer in a bottle of illuminating gas. In a bottle of carbon dioxide gas.

Experiment 7.—Submerge a tumbler in a pail of water, and while holding it suspended beneath the surface, strike it with a piece of metal so as to cause it to ring. The sound is transmitted through the water to the air and through the air to the ear.

Striking stones together under water.

EXPERIMENT 8.—Fasten the opposite ends of a long wire into the bottoms of cigar boxes or large pasteboard boxes, and hold one box against the ear while some one taps upon the box at the further end of the wire. Hold the wire suspended freely throughout its entire length.

The acoustic telephone.

EXPERIMENT 9.—Hold one end of a meter stick to the ear while some one scratches with a pin on the other end.

III. Reflection of Sound—Echoes.

EXERCISE 10.—How may we calculate the distance of a cliff or other reflecting object by the echo? (Sound has a velocity of 1,100 feet per second.)

Multiple echoes.
Roll of thunder.
Whispering galleries.
Acoustic properties of large audience rooms.

IV. Intensity of Sound and Amplitude of Vibration.

EXPERIMENT 11.—Strike a tuning fork first gently, and then hard, and touch it each time to the sides of a tumbler.

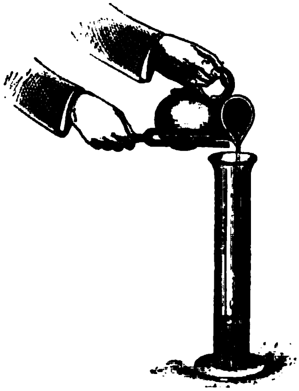

FIG. 2.

V. Resonators.

EXPERIMENT 12.—Hold a vibrating tuning fork over a tall cylinder about two inches in diameter (Fig. 2) and pour water into the cylinder until the air column has been reduced to such a length that it reenforces the sound of the tuning fork a maximum amount. Measure the length of the air column. When a prong of the tuning fork makes a complete excursion to and fro it is called one vibration. Why does four times the length of air column represent the wave length of the tone of the tuning fork? Knowing the number of vibrations the tuning fork makes per second, how would you calculate the velocity of sound? How do the number of vibrations affect the wave length?

Velocity of sound in air, liquids, solids.
Velocity of sound affected by temperature, moisture, etc.

EXPERIMENT 13.—While a tuning fork is vibrating, bring its stem firmly against the table top.

Sounding-boards.
Provision for resonators in stringed instruments.
Loudness of sound.
Large and small tuning forks.

VI. **Pitch.**

EXPERIMENT 14.—By blowing through the holes of a rapidly revolving wheel (Fig. 3), or drawing a card rapidly over the teeth of a saw, determine how pitch is related to rapidity of vibration.

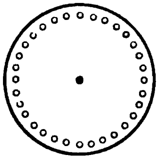

FIG. 3.

EXPERIMENT 15.—By means of a siren and piano, or tuning fork, determine the number of vibrations which correspond to a given tone.

EXERCISE 16.—If a locomotive is rapidly approaching or receding while blowing its whistle, how is its sound affected as to pitch?

VII. **Sympathetic Vibrations.**

EXPERIMENT 17.—Cause a large tuning fork to vibrate, and rest its stem for a moment upon a resonating box supporting another fork of the same pitch. Remove the first fork and listen for evidence that the second fork has taken up sympathetic vibrations.

VIII. Vibration of Strings.

Experiment 18.—By means of a sonometer find the relation of pitch to length, thickness, and tension of a wire.

Stringed instruments.
Overtones.
Harmonics.
Quality.

IX. The Musical Scale.

Experiment 19.—Examine the keyboard of a piano and be able to produce the scale—*do*, *re*, *mi*, *fa*, *sol*, *la*, *si*, *do*—beginning with any given key.

Questions and Problems

1. Why is it necessary to speak with greater effort to be heard on a high mountain than at the sea level ?

2. Why is it possible to hear so distinctly for a long distance through a speaking tube ?

3. What is an echo ? How far away must a reflecting surface be if sound, which travels at the rate of 1,100 feet a second, returns in 2¼ seconds after it is emitted ?

4. What evidences are there that pitch does not affect the velocity of sound ?

5. If sound travels at the rate of 1,100 feet a second, what is the wave length of a note that makes 512 vibrations a second ?

6. Why are the violin, piano, and other stringed instruments provided with sounding-boards ?

7. To what is the sound in wind instruments due ? How does the length of the instrument affect the pitch ?

8. In what respect may sounds differ from one another ? Upon what does the quality of a sound depend ? Illustrate.

9. Why does the addition of furniture and hangings sometimes better the acoustic properties of rooms ?

10. Name some of the principles of sound that are employed in the tuning and the playing of a stringed instrument.

TYPICAL ENTRANCE EXAMINATION QUESTIONS USED IN AMERICAN COLLEGES IN 1900

From six to ten questions required. Time allowed, about two hours.

(*a*) Explain why raindrops are spherical. (*b*) The simultaneous fall of bullet and feather in a vacuum. (*c*) Why oil which floats in water will sink in alcohol. (*d*) Why a suction pump will not draw water from a depth of 50 feet.

(*a*) Define energy. (*b*) What is the immediate source of energy in a water wheel, a clock, a dynamo? (*c*) Define the unit of work. (*d*) State the relation of machines to energy.

Give an example of each of the three states of matter, with a reason for the classification assigned.

What is meant by the moment of a force? Explain concisely why such a quantity is useful, and apply the principle in order to explain the value of the lever as a mechanical instrument.

Explain the distinction between mass and weight. Why does a body weigh less at the equator than at the pole? How could you find two equal masses?

State the law known as "the parallelogram of forces."

Define moment of force. What force in pounds applied at one end of a lever 10 feet long will lift a weight of 250 pounds at the other end, when the fulcrum is 2 feet from the weight end? 62.5

What are the units of mass, length, and volume in the metric system? How are they derived?

What is the relation between mass, volume, and density? State the difference between density and specific gravity.

How much work is done in lifting 5 kilos vertically through 500 cubic centimeters? State unit used.

What is the length of a pendulum beating seconds? ($g = 980.5$ cubic centimeters.)

Define what is meant by the center of gravity of a body.

What will be the velocity of a free falling body at the end of the fourth second?

How far will a body fall free during the fifth second of its descent?

(*a*) Give one method of finding the density of a liquid.

(*b*) A floating cube of wood, 3 centimeters on a side, displaces 20 cubic centimeters of water. Find the density of wood.

Explain the principle of a barometer. How does a water barometer differ from the common mercurial barometer?

Find the volume of air at a pressure of 76 centimeters which will become 50 cubic centimeters under a pressure of 165 centimeters.

How can the pressure of the atmosphere be demonstrated?

Why does a body weigh less when immersed in water than when it is in the air?

Upon what does the pressure of a liquid against the walls of a vessel depend?

What is the law of Boyle and Mariotte?

Describe Torricelli's mode of making a nearly perfect vacuum.

What are the fixed points of a thermometer, and how are they determined?

A brass rod at 0° is 1 meter long. What is its length at 100°, if the coefficient of expansion for brass = .00002?

Upon what does the boiling point of water depend? (Explain.) A mass of 200 grams of a solid at 100° is dropped into 500 grams of water at 10°, raising the temperature of the water to 13.5°. Find the specific heat of the solid.

(*a*) State the effects produced in water by rise in temperature from −5° to 100° C. (*b*) Define coefficient of expansion. (*c*) Define specific heat. (*d*) What is the mechanical equivalent of heat?

If heat be applied uniformly to ice initially at −10° C. until the temperature of the substance has risen to 15° C., what different effects will be noted, and what relative times will have been occupied in each process?

What general relation exists between the coefficients of thermal expansion of solids, liquids, and gases?

How is a mercurial thermometer made?

What is the relation of the Fahrenheit to the centigrade thermometer scale?

What is meant by specific heat? What substance is taken as the standard?

(*a*) State laws of magnetic attraction. (*b*) What is magnetic declination? (*c*) State how a body may be electrified without contact. (*d*) State defects in a simple galvanic cell and how remedied.

Show carefully how a Leyden jar is charged and discharged. What is the principle of the electro-magnet? Upon what does the strength depend?

Describe some simple experiments which would prove the laws of electrostatic attraction, and derive the unit of electricity therefrom. How is an electroscope charged by induction?

Explain the action of a galvanic cell. What is the difference between a Daniell and a Le Clanche cell?

What is the principle of the galvanometer? Describe one form.

State Ohm's law, and give an illustration of its use.

Explain in your own words the meaning and importance of Ohm's law. How can it be utilized to find the magnitude of the resistance of a given wire?

A battery of 15 cells in series sends a current through a galvanometer whose resistance is 10 ohms. If the potential difference and resistance of each cell are respectively 1.1 volts and 3 ohms, what current will be indicated?

Give an account of the action called electrolysis and of the laws which it obeys.

Describe some simple experiments which would illustrate the behavior of electro-magnetic induced currents of electricity. Show (using diagrams) that the action of the dynamo is based on an application of the laws of those induced currents.

Explain the principle of the secondary or "storage" cell.

Explain the construction and operation of the telephone.

What is the effect of a current of electricity upon a magnetic needle?

Describe a simple circuit for the Morse telegraph.

What are lines of force around a magnet?

Describe a two-liquid Voltaic battery.

(*a*) State laws of propagation of light. (*b*) Draw an image produced by a plane mirror. (*c*) Draw an image produced by a convex lens. (*d*) Define dispersion, conjugate foci, virtual image.

Tell how light is propagated. Show by diagram what is meant by index of refraction.

How is a spectrum formed? Upon what does the color of light depend?

Define principal focus of a lens. Draw diagram showing the formation of an image by a double convex lens when the object is outside the center of curvature. (Give reasons for your sketch.)

What two effects may be noted when light is passed through a prism, and what explanation may be given of them?

Explain how an image is formed by a concave mirror. When will the image be erect, when magnified, and when virtual?

How do spectacle lenses correct some common defects of vision?

What is the cause of color in bodies? What are complementary colors? Explain why the effect produced on mixing two colors is different from that produced on mixing two pigments of the same two colors.

Make a diagram illustrating the formation of an image by a concave mirror.

Make a diagram showing the formation of an image by a convex lens.

How are sound vibrations compounded? What is meant by the *interference* of sound waves? Show how the principle of interference accounts for consonance and dissonance in music.

(*a*) Explain the propagation of vibrations through air. (*b*) Define a wave length. (*c*) Explain echo. (*d*) What is the velocity of sound in air, and how determined?

What is meant by resonators in the study of sound? Discuss the apparent increase in the energy of the sound due to the presence of the resonator. What practical use is made of resonators?

How may each of the notes of the scale be successively produced on a single stretched cord?

What are the three characteristics of sound, and upon what does each depend? What are beats?

How can the velocity of sound in air be determined?

What are "overtones" and "harmonics"?

REFERENCE LIST OF EXERCISES, QUESTIONS, PROBLEMS, LAWS, FORMULAS, TABLES, DATA, ETC.,

To be found in Henderson and Woodhull's Text-book of Physics, and Woodhull and Van Arsdale's Laboratory Manual.

PROPERTIES OF MATTER AND MECHANICS OF SOLIDS

1. Exercises, Questions and Problems.
   Text-book, pp. 6, 14, 41, 52, 58, 63, 69, and 85.
   Manual, pp. 2, 3, 5, 8, 10, 11, 12, 13, 14, 15, 16, and 17.
2. Laws of Motion.
   Text-book, p. 72.
3. Formulas.

Velocity and momentum	Text-book,	p.	48
Acceleration	“	“	49
Falling bodies	“	“	56
Pendulum	“	pp.	61, 62
Work	“	p.	70
Machines	“	pp.	76–84

4. Tables.

Elements	Text-book,	p.	12
Hardness	“	“	16
Metric	“	“	25
Densities	“	“	42
Specific gravity of gases	“	“	44
Equivalents—English and metric systems	Manual	“	17

5. Units of C.-G.-S. System. Text-book, p. 52.

MECHANICS OF FLUIDS

1. Exercises, Questions and Problems.
   Text-book, p. 116.
   Manual, pp. 20, 21, 24, 27, 32, 34, 35, 36, 37, 38, 39, 40, 41, and 42.

2. Law of Boyle. Text-book, p. 112.
3. Formulas for area of circle, volume of cylinder, and volume of sphere. Manual, p. 42.
4. Table of specific gravity, weights, equivalents, etc. Manual, p. 42.
5. Weight of a litre of hydrogen. Text-book, p. 106.

Heat

1. Exercises, Questions and Problems. Manual, p. 61.
2. Laws

Of Charles	Text-book,	p.	161
“ fusion	“	“	164
“ boiling	“	“	170

3. Formulas

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“ correction of volume for temperature	“	“	161
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4. Tables

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Of mercury and glass	Text-book,	p.	158
“ gases	“	“	161
Temperature of the human body	“	pp.	163, 182
Five factors of evaporation	“	p.	166

Magnetism and Electricity

1. Exercises, Questions and Problems. Manual, p. 77.
2. Laws

Of inverse squares	Text-book,	pp.	219, 227
“ Ohm	“	p.	260

3. Formulas

For magnetite	Text-book,	p.	209
“ chemical action in Voltaic cell	“	“	238
“ battery solutions	“	pp.	242–244

For Ohm's law	Text-book,	p.	260
" Wheatston bridge	"	"	266
" arrangement of battery cells	"	"	268
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" variation in declination	"	"	217
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" "	Manual,	"	78
" specific resistance of metals to electric currents	Text-book,	"	268
" diameter of wire	Manual,	"	78

5. Essentials of the Voltaic cell. Text-book, 238.

Tangents explained	Text-book,	p.	262
Essential elements of a dynamo	"	"	280
Data for calculating resistance	Manual,	"	77

LIGHT

1. Exercises, Questions and Problems. Manual, pp. 83, 86, 87, 88, 89, 90, 91, 92, and 98.

2. Laws

Of inverse squares	Text-book,	p.	293
" reflection	"	"	304
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SOUND

1. Exercises, Questions and Problems. Manual, pp. 100, 101, 102, and 103.

2. Laws		
Of inverse squares	Text-book,	p. 352
" vibrating strings	"	" 358
3. Formulas		
For surface of a sphere	"	" 352
" musical scale	"	" 362
" vibration ratios	"	" 365
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Total number of experiments in the laboratory manual, 182.

Total number of figures in text-book, 259; in manual, 109.

Examination questions for entrance to colleges. Manual, p. 105.

Total number of exercises, questions, and problems in text-book and manual suitable for examination purposes, 214.

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